Cosmopolitanising technologies

J.J. Deuten

2003

Ph.D. thesis
University of Twente

Twente University Press

Also available in print:
http://www.tup.utwente.nl/

COSMOPOLITANISING TECHNOLOGIES

A STUDY OF
FOUR EMERGING TECHNOLOGICAL REGIMES

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Twente University **Press**

Publisher
Twente University Press
P.O. Box 217, 7500 AE Enschede, the Netherlands
www.tup.utwente.nl

Cover design: Martijn van der Rijken, Den Haag
Print: Océ Facility Services, Enschede

ISBN 90 365 1922 5

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PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. F.A. van Vught,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op vrijdag 20 juni 2003 om 13.15 uur

door

Johannes Jasper Deuten
geboren op 7 juni 1969
te Leeuwarden

Dit proefschrift is goedgekeurd door de promotor
prof. dr. A. Rip

en de assistent-promotor
dr. C. Disco

Preface

Doing PhD research and writing a dissertation has been an interesting experience in many respects. For one, when I started my PhD research in 1998 I could not have foreseen that I would write a dissertation with 'cosmopolitanisation' in the title. During the last years I have learnt a great deal, not only about knowledge production in technical domains, but also about knowledge production by myself as a PhD student in an academic setting. In this preface I'd like to take the opportunity to thank several people who have helped and motivated me while doing my PhD research. It is all too easy to lose one's agency somewhere along the PhD journey. Telling yourself forward cannot be sustained without the help and involvement of others.

First of all, I owe many thanks to Arie Rip. He is not only an inspiring supervisor, but also an excellent host and a good friend. I have enjoyed our sessions at the Lasondersingel in which we made a habit of mixing business and pleasure. Especially in the final months, when pressure was building up, Arie's productive comments and advice were invaluable.

I also want to thank Nil Disco and Wim Smit for their comments and suggestions in the first phase of my PhD journey when my research design had not yet crystallised. Nil's work has been an important point of departure for my ventures into the intriguing world of reinforced concrete. I am obliged to Wim also for his efforts to make arrangements for a somewhat prolonged stay at the UT.

Ibo van de Poel was so kind as to lend me his archives on paint. Unfortunately, I will not be able to return them as they were burnt to ashes (with the rest of my archives) in the big fire of November 20th 2002 which consumed our office and made the final months rather hectic.

In the first year I made a study trip to the Research Centre for Social Sciences at the Edinburgh University, enabled by a NWO travelling grant. I want to thank Robin Williams and his group for their hospitality. I hugely enjoyed my stay in Edinburgh.

I retain good memories of the workshops and summer & winter schools of WTMC. It was refreshing and stimulating to participate in them. I thank WTMC for its support in publishing this dissertation.

Working in the department of FWT has been a pleasure. I could not have wished for better roommates than Frank Geels and Adri Albert de la Bruhèze. I will miss my daily portion of wit, cleverness, and discussion. I am grateful that you wanted to listen to my stories about the Great War. Other colleagues also contributed to a good atmosphere at work, notably Barend van der Meulen and

Fokko Jan Dijksterhuis (thank you for the music). Hilde Meijer-Meijer and Gerdien Linde-de Ruiter gave vital practical assistance in meeting my deadlines.

I thank Martijn van der Rijken for his wonderful design of the cover.

Herman van der Kooij played a substantial role in making my time in Enschede enjoyable and in telling me forward during our lunchtime walks. Also many thanks for food & lodging.

Jan & Ali Deuten, thank you for your unremitting interest and support. Finally, I owe many thanks to Lisette Janse for her patience, friendship & love.

Enschede, May 20th 2003

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Chapter 1.
Introduction

1.1 Introduction of theme and research questions

New technologies are born as 'hopeful monstrosities', their form and function still being tentative. Often they are not fully understood as to why they work. Disco (1990), in his study of technological closure linked to professional closure, discusses the case of reinforced concrete. In the 1850s, reinforced concrete emerged as a further variant of "strengthening structures made of drying or setting mortars by inclusion, in the wet mortar, of fibrous or other materials having a high tensile strength. Mud houses, daubed huts, adobe bricks, all gain structural integrity from this technical ploy." (Disco, 1990: 274). The French gardener Joseph Monier, in 1867, patented the use of reinforced concrete for plant tubs, and later expanded its use to pipes, reservoirs, plates, bridges and stairs (275). While Monier probably did not understand the exact role of the iron reinforcement, this "did not prevent him from actually producing structures in this new technology. It is this practical activity, by means of which Monier *demonstrated*, rather than simply argued, the viability of reinforced concrete (RC), that justified his patent rights (…). However "unscientific" Monier's designs may have been, it became clear that he had developed a commercially workable technology which showed promise both of transforming and cheapening existing building practices." (277).

> "On the basis of his "universal" 1878 patent he was able to licence "Monier" companies in Germany, Austria, England and Belgium. This dispersion, however, meant that the technology had to be adapted to new environmental demands: not only physical conditions like climate, typical building sites, or the types of raw materials available, but also socio-political ones like the nature of the demand and, particularly, national and municipal building codes. These new opportunities and constraints placed a premium on learning to control the new technology, both for the purposes of expanding its applications in predictable ways, as well as for the purpose of satisfying government building standards. Thus developed a synergistic relationship between ambitious RC contractors and exacting government regulatory agencies aimed at mastering the theory and practice of RC construction. (…) From then on, RC developed internationally along three simultaneously expanding fronts: actual RC constructions, experimental tests, and theoretical-mathematical modeling." (277).

Disco's interest in this case is to show how actors, in particular engineers, appropriate a new and at first uncertain technology, to serve their interests, including maintenance of professional authority. He notes also how

> "perception of new technological opportunities (…) gives rise to specific *technological* communities composed of organizationally dispersed engineers (…). (…) The technological community reduces *substantive* risks by pooling local experiences, deliberating on the implications of such experiences for the management of the technologies, and ultimately by formulating collectively sanctioned modelling procedures and practical algorithms, sometimes in the form of codified standards and procedural rules." (269).

These brief quotes serve to introduce my theme: technologies are not born generally applicable, and in that sense 'cosmopolitan'. They have to be *made* cosmopolitan, and such efforts have their own dynamics, professional and otherwise. Further inquiry into such processes of cosmopolitanisation (to introduce a new and difficult to pronounce word) is necessary.[1] There are already insights into these processes on which I can draw, but they have their limitations.

In many studies on technological change, and in the thinking of technologists, new artefacts and the eventually dominant designs are foregrounded (e.g. Tushman and Anderson, 1986). But these artefacts and designs are based on technological knowledge and skills, and a dominant design can only be 'dominant' if the relevant technological knowledge is available to all relevant actors. In the literature on technological regimes (which broadens and sociologises the literature on dominant designs), this point is recognised, but only rarely discussed as such (e.g. Van de Poel, 1998; Nelis, 1998; Van den Ende and Kemp, 1999). But this is necessary, because technological knowledge and skills cannot simply be shared: they start out as local knowledge, and have to be articulated and transformed so as to become transferable, in other words, so that they can travel. And secondly, there are costs involved in such transformations and circulations, and it is not obvious why actors will invest in the production of what is essentially a collective and somewhat public good. There is always an ambivalence between keeping knowledge local and making it available. This was already visible in the European Renaissance with so-called 'professors of secrets'. "They collected recipes from different crafts and some of their own experience, and sold them at the fairs or to sponsors. (…) They had to advertise themselves and their knowledge in order to create some visibility. However, at the same time they had to keep their secrets in order to maintain a competitive advantage over other such 'professors' operating at the same market or for the same sponsors." (Rip, 2002a: 133 referring to Eamon, 1985). Nowadays, biotechnologists and other technologists and scientists in commercially important areas face a similar ambivalence in their position.

Thus, how can sharing, the essential step towards the emergence of a technological regime, occur at all? And when it occurs, can we understand why, and

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[1] Disco *et al.* (1992) introduced the concept of cosmopolitan in technology studies. They derived it from Gouldner (1957) who used it to refer to social roles of humans within organisations rather than knowledge or technology. Gouldner's 'cosmopolitans' orient themselves on their profession, whereas 'locals' orient themselves to their own organisation.

how it will be shaped? These are the questions I want to address in this PhD thesis.

The local and heterogeneous nature of technological knowledge

My first point of departure is that technological knowledge is local in origin, and requires articulation and transformation in order to be transferable and shareable, e.g. within technological regimes. Rip and Kemp (1998) define technology as configurations that work. It follows that technological knowledge is about making configurations that work and about making these configurations work. Often, technological knowledge is also about how or why configurations work, and about what work configurations should do.[2] Configurations can exist at different levels of complexity or systemicness in a "technological hierarchy" (Disco *et al.*, 1992: 485). On the first level there are "components (e.g. materials, nuts and bolts, resistors and condensers, radio vacuum tubes) that do not 'perform' by themselves, but have to be assembled to do their job". At the second level there are "devices (e.g. a pump, a switching circuit, a sensor) that are assembled sufficiently to show their primary effect". At the third level there are "functional artefacts (e.g. a machine, a bridge, a radio) that work by themselves", and at the top-level there are "systems (a plant, an electricity network, radio broadcasting plus receivers plus organizations to produce radio programmes) that fulfill a sociotechnical function." When technological knowledge is about making configurations that work, it is immediately clear that this works out differently at different levels. The formulation of a material (e.g. reinforced concrete or paint) requires a different kind of technological knowledge than the construction of a system (e.g. an air traffic control system). Despite this varied nature of technological knowledge, it is to a large extent *practical* knowledge — geared to solving problems in concrete situations. This is a main source of locality. While scientists explicitly try to produce knowledge which transcends local

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[2] It is not automatic that knowledge about how or why configurations work is generated. To make configurations that work, it is sufficient to have operational principles that work. At the same time, there is a secular trend in which it is assumed that basic "know why" is useful, e.g. because it might lead to better and further operational principles. Technological knowledge, however, is always more than ("applied") scientific "know-why" knowledge, because there always is a tension between the design and the actual realisation of the design in the real world.

Dasgupta (1996) makes a distinction between basic knowledge (that emanates directly from scientific realms), technological theory (which resembles basic knowledge but its scope of applicability is more restricted to specific technological domains), and technological knowledge (which basically consists of operational principles). Sources of operational principles are design as invention, experiments, experiences, and derivations from basic knowledge or technological theory. Dasgupta emphasises that operational principles can and do work in tandem with science and theory. An operational principle which is based empirical studies, observation, or experience can induce research into its underlying causes, which can result in scientific and theoretical knowledge. Through compilation and abstraction this can, in turn, generate new operational principles. The example of the zipper, however, shows that technological knowledge can remain on the level of operational principles for a long time, and still support innovation (Friedel, 1994).

contexts, engineers do not necessarily have this intention. What matters is whether technology works; not if knowledge is valid in other contexts.[3]

The (initially) local character of technological knowledge has been recognised by many authors that have written on technological knowledge. Eric von Hippel (1994), for example, uses the term 'sticky knowledge' to indicate the connectedness of knowledge to the local context and its problematic movability.[4] Eugene Ferguson (1994) stresses the importance of practical, nonverbal and tacit characteristics of technological knowledge. At the same, it is also widely recognised that there also is general and decontextualised technological knowledge, such as formal engineering knowledge that is taught at technical schools and universities. Trained engineers, for instance, are acquainted with general and abstract technological knowledge, a sort of reservoir that they can apply to a whole range of (somewhat similar) technical problems. Such application or recontextualisation, however, is not self-evident and requires skills and tacit knowledge.[5] Thus, technological knowledge can have different degrees of contextuality and generality.

Technological knowledge is heterogeneous also because it has to serve a practical purpose. There are rules of various kinds to make technological configurations work, attempts to understand the nature of the configuration in terms of a "technical model" (Disco *et al.*, 1992) or the "principle of its operation" (Vincenti, 1990), and various bits of relevant engineering and scientific knowledge. The heterogeneity is visible in Staudenmaier's well-known classification of technological knowledge. Staudenmaier (1985) distinguishes technical skill, data gathered to solve specific technical problems, heuristics, engineering theory, and scientific concepts. The first two types of knowledge are highly context- or configuration-specific, whereas the latter three are more general, abstract and decontextual.

Vincenti (1990) makes a similar classification in which he identifies six hierarchical categories of engineering knowledge. On the highest level there are fundamental design concepts such as what he calls the 'operational principle' (how the configuration basically works) and the 'normal configuration' (the general shape and arrangement that are commonly agreed to best embody the operational principle) which are sufficiently decontextual to be widely shared

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[3] It can immediately be added, however, that technologists who address several contexts, might want to produce knowledge which is not context-bound and configuration-specific. Stankiewicz (1992) distinguishes between the roles of engineers and technologists. Engineers primarily apply existing technological knowledge to specific and concrete problems, while technologists are oriented towards developing solutions to classes of problems by generating more general and basic know-why.

[4] Sticky information is hard or impossible to replicate and diffuse to remote sites. Reasons for the stickiness of data include that the data may involve proprietary information (e.g. trade secrets), they may represent tacit knowledge, or they may be indexed in a form difficult to transfer (Von Hippel, 1994).

[5] This also happens within scientific research, see Collins (1985) on building a TEA laser.

within a technical community.[6] On the next level there are criteria and specifications. Design criteria are based on the translation of general qualitative goals into quantitative goals couched in technical terms — an activity which is at the core of engineering. When criteria and specifications are made to apply to a class of configurations rather than specific configurations, for instance when specifications become part of (safety) regulations, they become part of the "stored-up body of knowledge" in engineering (Vincenti, 1990: 212).

Vincenti further identifies theoretical design tools which include intellectual concepts for thinking about design as well as mathematical methods and theories for making design calculations.[7] Quantitative data (prescriptive or descriptive) form the next category of technological knowledge. These data often been created empirically, and are typically represented in tables or graphs. The fifth category consists of practical considerations which are primarily derived from experience, and suggest the designer how to go about achieving a required design. Such knowledge often takes the form of design rules of thumb. Vincenti adds that "[o]ccasionally practical considerations become well codified and are more logically put in another category", which implies that categories of knowledge are not mutually exclusive and sometimes grade into one another (Vincenti, 1990: 219). Finally, there are design instrumentalities, which refer to "knowing how" or "procedural knowledge".

While Vincenti's classification does highlight the heterogeneity of the various categories of technological knowledge, it also imposes a hierarchy which suggests a deductive relationship, or at least a difference in cognitive status. Such an attempt at stratification is attractive to engineers, who see themselves as responsible for the higher levels. Disco (1990) has pursued this point. Importantly, the quotes from his PhD thesis which open this chapter, show that the higher levels appear later in the evolution of a technology, and in that sense depend on the lower levels and their articulation and aggregation.

Van de Poel (1998) created a scheme to locate the various kinds of knowledge which allows the dynamics to be traced. His hierarchical 'triangle' (Figure 1.1) "encompasses a top-down, as well as a bottom-up dynamics: from goals, principles, promises and requirements to artefacts, and from the actual realization of artefacts and the problems (and sometimes new possibilities) involved to shifts in requirements and goals." (Van de Poel, 1998: 17).

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[6] The decontextuality of operational principles and normal configurations is an achievement of the engineering community and is based on selection of, and agreement on, best variations.

[7] Vincenti (1990) identifies a broad spectrum of (mathematical) methods and theories: purely mathematical tools; mathematically structured knowledge (that is essentially physical rather than mathematical); device-restricted theories (based on scientific principles but motivated by and limited to a technologically important class of phenomena or even to a specific device); phenomenological theories (that serve almost solely for engineering calculation); and quantitative assumptions introduced for calculative expedience.

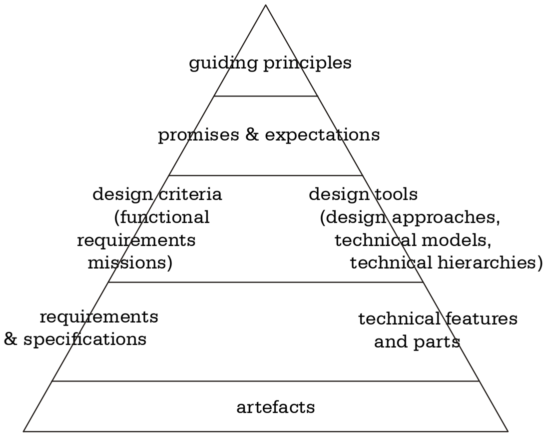

Figure 1.1 The triangle of technological development (Van de Poel, 1998: 17)

Located at the top of the triangle are 'guiding principles', while 'promises and expectations' are located at the second level. When these are shared in a technological regime, they guide the development of new artefacts and provide a framework for development and use of technological knowledge on lower levels in the hierarchy. On a third level there are 'design criteria' and 'design tools'. Criteria broadly define the kind of functions or functional requirements to be fulfilled by an artefact and the kind of boundary conditions that are important in the design of a technology. Design tools are used to translate functions into requirements and include design heuristics, technical hierarchy, technical models, design tools to evaluate whether particular artefacts fulfil their intended function, and design methods and approaches.[8] The next level consists of 'technical features and component parts' on the one hand, and 'requirements and specifications' on the other hand. In the bottom of the triangle are artefacts which are "the embodiment of the alignment of functions and technical configurations that is typical for a technological regime" (18). The different types of technological knowledge in Van de Poel's scheme are aligned to each other. If one of them changes, sooner or later, others have to change as well. Transformations in the elements require processes of negotiation, coordination and technical agenda building. While the scheme, and its visualisation as a triangle,

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[8] Van de Poel (1998) — drawing on Disco *et al.* (1992), Vincenti (1990), Constant (1980) and Clark (1985) — describes design heuristics as "inter-subjectively sanctioned rules suggesting the direction in which a good solution to a design problem can be found"; technical hierarchies as " the subdivision of the artefact to be designed in devices and components"; technical models as "representations of a class of technical artefacts showing their (underlying) structure and function (…); evaluative design tools include "tools to enable tests (prototype, test facilities), but also calculation and simulation tools"; and design methods and approaches "which guide the designer(s) through the different phases of the design process." (18).

has a hierarchical slant, Van de Poel emphasises the co-evolution of function and form, which can start from and be concentrated on any of the levels. Over time, a design hierarchy (Clark, 1985) can emerge and stabilise, but this is an outcome, not a precondition.

Thus, dynamics are important. For each of the categories of technological knowledge in these various classifications, one can ask how translocal they are or have become. This is an empirical question, even if some categories tend to be more general and decontextualised than others.

On the one hand, translocal is what *transcends* the local, and is decontextualised — seen from the point of view of a specific local context. It is not completely context-free, however, since translocal knowledge is (re-)situated in a cosmopolitan context (like that of a technological community, cf. Disco, 1990). Translocal knowledge cannot exist in a vacuum, but is part of a knowledge reservoir which is actively produced and maintained. On the other hand, translocal is also what *bridges* localities, through a productive combination of decontextualisation (with regard to original locations) and recontextualisation (with regard to new localities). In any case, to achieve translocal knowledge requires work, and work of different kinds. For instance, work has to be done to make knowledge movable (decontextualisation and packaging), to let it move (infrastructure) and to make it work elsewhere (recontextualisation, standardisation).

I will argue that translocality is a socio-cognitive and socio-political achievement and that these two dynamics are entangled, and may well be inseparable. In the literature, they tend to be treated separately, where negotiations about standards and interoperability (as in the economics and sociology literature) neglect the cognitive aspect, and historians and philosophers concentrate on the cognitive, backgrounding the complexities of real world.

Shared technological knowledge as a collective good

Translocal knowledge is shared knowledge, by definition. The sharing can be limited to a small group of directly interested actors, for example the various companies in Monier's reinforced-concrete imperium. A number of studies have been done on the conditions for sharing knowledge in emerging as well as stabilised industries (see 1.2.6 and 2.3.2 for a discussion). As is clear in the case of reinforced concrete, there are other relevant actors besides industrial actors, in particular government agencies requiring data on quality and reliability of the new technology. Sharing also occurs in a "technological community" (Disco, 1990), even if concrete details might be excluded from the sharing (or be limited to bilateral exchange relationships). The net effect is that knowledge becomes available to a variety of actors, somewhat independently of specific exchanges.[9] A reservoir of more or less accessible knowledge is created, maintained and added to. Access is related to rights (e.g. licensing), to expertise (absorptive capac-

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[9] Cf. economists on "spillover effects" of codification (e.g. Breschi and Lissoni, 2001).

ity)[10] and to membership (in the relevant community). When accessing the reservoir, knowledge is taken up, but not consumed in the traditional sense, where the good will be gone after it has been consumed. The knowledge is "non-rival" and remains available for consumption by others.

Such knowledge reservoirs emerge but can also be pursued actively. They are carried by social networks, technological and professional communities, and are in that sense a collective good. Economists and some political scientists will ask about the incentives to participate in the production of such a collective good, and rightly so. Sociologists add that a shared repertoire helps to define identity and position, even while it will not determine them once and for all. In that sense, the process is not different from how shared cultures or just subcultures) emerge and members of that culture will draw on the shared repertoire.

The similarity with culture as a repertoire indicates that the shared repertoire of technological knowledge is not just a collective good that can be used or not. It also shapes thinking and action, as the concept of 'regime' implies. Swidler (1986: 273) conceptualised culture as "a repertoire or 'tool kit' of habits, skills, and styles from which people construct 'strategies of action'." Repertoires overlap and exist at individual and collective levels. Institutions are one source of systematic 'cultural logics' (as overarching and unified grammars that shape thinking and action), but "culture and institutions are "reciprocal" not homologous." (Swidler, 2002: 3). That is, institutions (e.g. marriage) set the scene, and actors may have to solve problems created, shaped or at least pre-structured by the cultural logic of the institution. In doing so, they draw on culture for various resources, including rich repertoires of alternative meanings.[11]

What is not clear in Swidler's and others' work is how cultures evolve, and how cultural logics change. One way to conceptualise changes is through the notion of paradigms, as Dosi (1982, 1984) used the term to indicate a set of shared heuristics which guide a technology along a trajectory.[12] He did not pursue the parallel with scientific paradigms so as to consider revolutionary changes, but Constant (1980) argued that a paradigmatic change is precipitated by the identification of a "presumptive anomaly" — the presumption that at-

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[10] The concept of "absorptive capacity" was introduced by Cohen and Levinthal (1990) to indicate that firms need to invest in research and development in order to be able to use results from research and development performed by other parties. It also applies to individuals and their competencies.

[11] One way in which institutions shape is through the 'semiotic codes' they entail. Over and above specific institutions, there are widely available habits and collective action schemas, which may add up to national styles (Swidler, 2002: 4).

[12] Dosi (1982) described a technological paradigm as "an outlook, a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution" (148) and as a "model and a pattern of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies. (...) We will define a *technological trajectory* as the pattern of 'normal' problem solving activity (i.e. of 'progress') on the ground of a technological paradigm. (...) [A] technological paradigm (or research programme) embodies strong prescriptions on the *directions* of technical change to pursue and those to neglect." (152; emphasis in the original).

tempts to extend the existing paradigm to a new set of problems will fail to provide "satisfactory" answers. In other words, it is a presumptive anomaly which leads to a new paradigm and a new "normal practice". This alternation of established paradigm, a fluid period of change and a new paradigm fits with the literature on dominant design (Abernathy and Utterback, 1978), but is too specific to use as a general point of departure.[13]

Neglecting these complexities for the moment, one can say that knowledge reservoirs are a collective good, and ask how they are created. Mancur Olson Jr. (1965: 2) has argued convincingly that "[u]nless the number of individuals is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, *rational, self-interested individuals will not act to achieve their common or group interests*." The production of collective goods requires institutional arrangements and mechanisms. Especially in emergent situations as with new technology, this will be difficult since there will be uncertainties.

While I phrase the question in terms of a collective good and how this can be produced, the issue is broader than the treatment it gets in the economics literature. Economists focus on individual actors and wonder how a collective good can be produced at all, given the lack of adequate returns for the individual actor. From a sociological perspective, the production of collective goods is a process of institutionalisation. Not only because the production of collective goods requires institutional arrangements, but also because collective goods themselves are institutionalised and shape actions and interactions. Indeed, many institutions are collective goods (to the extent that they serve a collective interest and are non-rival and non-exclusive).[14]

Thus, cosmopolitanisation can be studied as institutionalisation of technological knowledge. Then it becomes important to assess what relevant sociological literature has to say about such emerging institutionalisation processes.

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[13] At the start of a "product life-cycle" at the industry-level, a variety of product designs are being developed. The competition between designs is eventually resolved into a dominant design. Subsequently, innovation concentrates on process innovation and incremental product innovation given the dominant design — cf. "natural trajectory" (Nelson and Winter, 1977) or "technological trajectory" (Dosi, 1982).

[14] An example of institutionalisation of a collective good is the establishment of surveillance organisations (e.g. in stock exchange) which are collectively funded by the parties that are being surveilled.

1.2 A survey of literature

In this section, I present a selection from the relevant literature, starting with Anthony Giddens on structuration.[15] His ideas provide me with a global framework to consider what happens in emerging technological regimes — the context in which technological knowledge is (or is not) institutionalised and cosmopolitanised. For processes and mechanisms that are involved I turn to other authors. Obviously, my discussion of these authors and approaches can only address the tip of the icebergs of these literatures. I offer short summaries, in which I will highlight aspects which are relevant for my questions. Recurrent themes are emergence of structures and institutionalisation in heterogeneous multi-actor situations, which then lead to multi-level approaches (Elias, 1978 in section 1.2.4; but also Van de Ven and Garud, 1989, in section 1.2.6). While technological regimes are discussed specifically, they are positioned as a case of the overall approach of processes and mechanisms of structuration.

1.2.1 Structuration theory (duality of structure)

In Giddens' (1984: 2) view, social science has to study the ordering of social practices across space and time. Institutions are an example of such an ordering with "the greatest time-space extension" (17). Thus, his structuration theory is relevant for studying the institutionalisation and cosmopolitanisation of technological knowledge. Giddens defines structuration as "the structuring of social relations across time and space, in virtue of the duality of structure" (Giddens, 1984: 376). The *duality of structure* means "that social structures are both constituted *by* human agency, and yet at the same time are the very *medium* of this constitution" (121). In other words, social structures are both the outcome as well as the means of social action.[16] Structures exist only to the extent that they are constantly sustained and reproduced by human activity. At the same time, social structures also produce and sustain the actors who are producing and sustaining them. Thus, actors and structures define each other.

> "Analysing the structuration of social systems means studying the modes in which such systems, grounded in the knowledgeable activities of situated actors who draw upon rules and resources in the diversity of action contexts, are produced and reproduced in interaction." (Giddens, 1984: 25).

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[15] Giddens' structuration theory aims to explain and integrate agency and structure. It studies the ways in which social systems (e.g. regimes) are produced and reproduced in social action and interaction. According to the theory of structuration, "the basic domain of study of the social sciences (…) is neither the experience of the individual actor, nor the existence of any form of social totality, but social practices ordered across space and time. Human social activities (…) are recursive. That is to say, they are not brought into being by social actors but continually recreated by them via the very means whereby they express themselves *as* actors. In and through their activities agents reproduce the conditions that make these activities possible." (Giddens, 1984: 2).

[16] Structures are defined as recursively organised sets of (normative and cognitive) rules and (authoritative and allocative) resources (Giddens, 1984).

It is enacted human conduct in the form of structured practices that maintains, reproduces and changes social structures. In other words, structures and structured practices co-evolve. Changes in practices (either because individuals make conscious decisions to change, or through less conscious forms of adjustment, adaptation, and practice) can result in changes in structures, e.g. through collective action or through parallel changes by local practices. The emergence of new or adapted social structures begins with enacted practices which evolve into institutions or routines which are reproduced in social action — and become enabling and constraining.

Structuration is a result of stabilisation of interdependencies and interaction patterns across time and space. The question, therefore, is how it comes about that social activities become 'stretched' across wide spans of time-space. For Giddens this "time-space distanciation" is part of modernisation and refers to the "lifting out" of local practices from narrow definitions of time and space.[17] I.e., they are decontextualised. Stretching can occur in various ways: actors can circulate and meet (and communicate) in forums; or they can remain in the local contexts and use infrastructures to communicate. More generally, time-space can be stretched by "disembedding mechanisms": the lifting-out of social relations from local contexts and their *rearticulation* across indefinite tracts of time-space.[18] Giddens defined "disembedding" of social systems as a *removal* of social relations from their locality and the *reassembling* of these relations in another time-space. It is dependent upon two concepts that have played a large role in modernisation: the acceptance of symbolic tokens and expert systems. Symbolic tokens are media of exchange which have standard value, and thus are interchangeable across a plurality of contexts (e.g. money). The acceptance of a token made of a material with no real value under the assumption that it can be traded for something of value relies on trust. When such trust universally exists, a token provides for a bracketing of time and allows for exchange to occur outside of local spaces. Expert systems, in their turn, bracket time and space through deploying modes of technical knowledge which have validity independent of the practitioners and clients who use them. Their role as disembedding mechanism depends on their ability to produce knowledge which can transcend specific tracts of time-space. Expert systems also rely on trust, that is trust in universality of knowledge.

I will use Giddens' (1984) notion of duality of structure as a theoretical base for my conceptualisation of how technological knowledge becomes shared. Institutionalisation of technological knowledge can be understood as structura-

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[17] Giddens notes how the introduction of standardised time played an important role in the separation of time and space (Giddens, 1991).

[18] Modernisation is characterised by an increasing use of disembedding mechanisms to organise social life. At the same time, re-embedding occurs in which disembedding mechanisms are pinned down to local contexts again (Giddens, 1991).

tion, in which technological knowledge becomes part of a structure which (increasingly) enables and constrains local activities. Following Giddens, the question of how such a structure emerges and stabilises should be analysed in terms of stretching of time-space and disembedding: the lifting out of knowledge production from local contexts. Key concepts are disembedding, rearticulation and reassembling which indicate that local knowledge has to be reshaped in a form that can circulate in time-space which enables technological regimes to emerge.

Giddens' theory is general and abstract, and not geared to answering my specific questions on translocality and production of translocal technological knowledge as a collective good. Nevertheless, Giddens' insights on how social structures are both the means as well as outcomes of social action, offer a point of departure for my study on technological knowledge — taking translocal knowledge as both medium and outcome of interaction. New collective knowledge reservoirs (as parts of structures) will co-evolve with local practices which produce and reproduce such reservoirs. In addition, institutionalisation and cosmopolitanisation of technological knowledge can be understood as part of modernisation processes.

Rammert (1997) provides an interesting application of structuration theory to technology ("techno-structuration"). Although he does not take up the issue of how translocality is achieved explicitly, he offers valuable insights on how technology becomes part of a techno-structure — which is both the medium and product of actions. When a locally established variant is widely imitated, transferred to other regions and globally reproduced, this leads to stabilisation across space.[19] If successive technology projects follow the heuristics used earlier, typical trajectories of technical development are constituted, leading to stabilisation over time (Rammert, 1997: 186). To understand what Rammert calls 'techno-structuration', the first step is to study how new technological schemata are carved out of everyday routine action by inventors, researchers and users. The second step is to understand how recursive actions associated with artefacts lead to techno-structures, how they grow from local associations to global technical systems, and how they gain stability and reproductive continuity (175). Rammert makes an interesting point when he argues that

> "[a]t all times technological rules and concepts are being developed from 'competent and controlled inquiry' and 'reflective experiences' (…). Nowadays, most of them originate from professional invention and organized research. Decontextualized from everyday life's routine action, technological rules are turned to abstract engineering rules and technological concepts and are incorporated in machines and technical systems. (...) However, they can only function as a means to improve action when they get recontextualized into the social worlds of routine action (175).

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[19] Note that for imitation and transfer to occur, translocality must have been achieved, or be worked on.

In other words, decontextualisation and recontextualisation are part and parcel of techno-structuration. Techno-structuration occurs when procedures, tools and prototypes are constructed and experimented with, and the "technological experiences thus gained are collected selectively in handbooks and presented at congresses with the intention of demonstrating an unproblematic feasibility and of suggesting superior efficiency." (181).

Affordance-based explanations

Taking structuration as the theoretical base has implications on how cosmopolitanisation should be understood and explained. It is clear that a causal factor-type explanation will not suffice, not in the least because Giddens (1984: 11-12), following Merton (1936, 1963) and referring to Olson (1965), emphasises that unintended consequences are inextricably bound up with social action.[20] A better mode of explanation is in terms of affordances. Affordances are available in the environment and shape actions, without determining them. Factor-type explanations then appear as a special case, where affordances are constraining, and continue to be so. Affordance-based explanations are compatible with emerging path-dependencies and irreversibilities, because actions and interactions may modify the affordance structure.

The notion of affordance was used by Gibson (1979) in his study of how animals perceive their environments and act on it. For example, if a terrestrial surface is nearly horizontal (instead of slanted), nearly flat (instead of convex or concave), and sufficiently extended (relative to the size of the animal) and if its substance is rigid (relative to the weight of the animal), then the surface affords support. Thus, a surface will afford support differently for different animals (Gibson, 1979: 127). In other words, affordances have functional as well as relational aspects.

The notion of affordances has been used in design studies (Norman, 1990). In this domain, an affordance refers to an object's suggested use. For example, "a button, by being slightly raised above an otherwise flat surface, suggests the idea of pushing it; a lever, by being an appropriate size for grasping, suggests pulling it; a blinking red light and buzzer suggests a problem and demands attention; a chair, by its size, its curvature, its balance, and its position, suggests sitting on it."[21] Recently, Hutchby (2001) has introduced the concept

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[20] "Merton has provided perhaps the classical discussion of the issue. He points out, entirely correct, that the study of unintended consequences is fundamental to the sociological enterprise." (Giddens, 1984: 12).

[21] *Usability glossary* (www.usabilityfirst.com/glossary). In design literature, the term affordance refers to "the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used (..). A chair affords ("is for") support and, therefore, affords sitting. A chair can also be carried." (Norman, 1998: 9). Affordances invite as well as constrain us in our handling of things.

of affordance to analyse the technological shaping of sociality.[22] He argues that "affordances are functional and relational aspects which frame, while not determining, the possibilities for agentic action in relation to an object." (Hutchby, 2001: 444).

In terms of (shared) cultures and repertoires (Swidler, 1986), affordances might be understood as "cues for action" (DiMaggio, 1997). Since the cultures into which people are socialised leave much opportunity for choice and variation, the attention turns to "ways in which differing cultural frames or understandings may be situationally cued."(2). In other words, cultural cues available in the environment guide selection. Cultural frames or schemata can be activated through conversation, media use, or observation of the environment. "Understanding the interaction between two distributions — of the schemata that constitute people's toolkits, and of external cultural primers that act as frames to evoke (and, in evoking, exerting selection pressures upon) these schemata — is a central challenge for sociologists of culture." (8). DiMaggio does not elaborate on the cues, how these emerge and continue to "act as frames". But one can study which cues are available in a certain environment and show that they function as an affordance structure.

I will use affordance structures in a similar way, to understand why actors in certain situations will or will not, whether intentionally or unintentionally, contribute to socio-cognitive structuration. The affordance structure is in the situation, and frames possibilities for action while not determining them. The metaphor of a landscape with gradients is useful. In a landscape, some routes are more traversable than others. Why climb over steep mountains, if you can follow a path through a valley (if you know the valley is there)? The routes which will be chosen not only depend on characteristics of the landscape, but also on characteristics of the traveller (e.g. is she experienced, strong, adventurous, etc?). Also the fact whether certain routes have been traversed before (by others or by oneself) can determine the traversability of a landscape — this captures the phenomenon of path-dependencies. Rather than incentives which reward or punish, affordances suggest directions of action — which might work out differently for different actors. Moreover, the suggestive force of affordances might increase as the landscape is traversed increasingly and patterns become visible for (new) travellers.

Outcomes, in terms of shape and extent of cosmopolitanisation will be created by an "array of affordances" (Hutchby, 2001: 452). Part of the force

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[22] Hutchby (2001) proposes "an approach to the study of technologies and social life which offers a reconciliation between the opposing poles of constructivism and realism. This involves seeing technologies neither in terms of their 'interpretive textual' properties nor of their 'essential technical' properties, but in terms of their *affordances* (Gibson, 1979)." Using the concept of affordance, "technologies can be understood as artefacts which may be both shaped by and shaping of the practices humans use in interaction with, around and through them. This 'third way' between the (constructivist) emphasis on the shaping power of human agency and the (realist) emphasis on the constraining power of technical capacities opens the way for new analyses of how technological artefacts become important elements in the patterns of ordinary human conduct." (Hutchby (2001: 444).

stems from the "array", rather than that it is just a summing up of separate affordances.

1.2.2 Social rule system theory, actor-centred institutionalism, and social network theory

Social rule system theory

If institutionalised technological knowledge is conceived as a cognitive rule, structuring the actions and interactions of actors within a technological regime, then social rule system theory (Burns and Flam, 1987) is relevant for my conceptualisation of the emergence and institutionalisation of translocal technological knowledge — even if the theory foregrounds social rules, rather than cognitive rules. Social rule system theory shares several features with the meta-theoretical and ontological features of Giddens' structuration theory, such as the concept of knowledgeable agents, their active engagement in rule processes and the reproduction and transformation of social structure, the duality of structure, the recursive nature of human activity, and unintended consequences of human action. "In contrast to Giddens' work, however, the framework provides the basis for a programme of systematic, empirical research and the tools to formulate general models and subtheories of particular types of social organization and the processes whereby they are formed and reformed." (Burns and Flam, 1987: 389). Social rule systems are a three-level phenomenon: the micro-level of actors, their roles and positions; the meso-level of social action and interaction settings and processes; and the macro-level of (endogenous) constraints which are institutional, cultural and material.

In social rule system theory, rules are continually reproduced by actors who interpret, implement and reformulate the rules which enable and constrain their actions and interactions. Unintended consequences play an important role as the emergence and transformation of social rule systems can be understood as the unintended aggregate outcome of individual and subgroup innovations (novelty), entrepreneurship, or deviant behaviour. The accumulation of local adaptations (to novelty), changes and innovations leads to ambiguities, uncertainties and conflicts with regard to rules on a collective level. On the other hand, the framework also focuses on processes of "strategic structuring" in which agents interact — struggle, form alliances, exercise power, negotiate and cooperate — within the constraints and opportunities of existing structures. While the theory stresses the ability and competences of innovative actors to mobilise sufficient social power and other resources (like capital, expertise, infrastructure, legal rights, political support, etc.), strategic structuring does not happen in a vacuum, but is itself conditioned by existing rule systems. In their shaping and reshaping of social structures and institutions and the material circumstance, actors are (and remain) subject to material, political and cultural constraints. In sum, social rule systems emerge and transform as a result of intended and unintended outcomes of action and interactions.

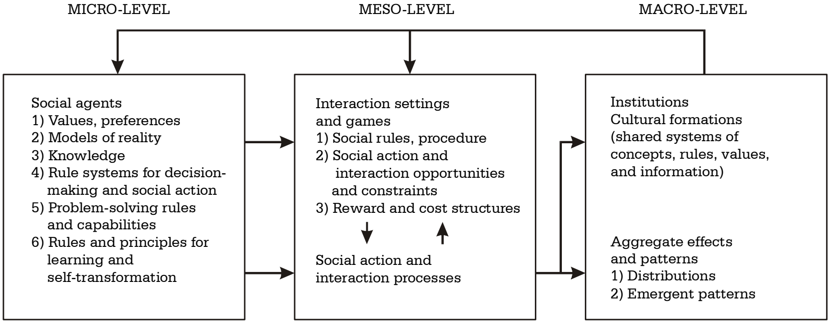

Figure 1.2 Model of multi-level social system (Burns and Flam, 1987: 5)

There are two main sources of unstability. First, there are "exogenous factors" that impact on rule systems. These include secular changes. Second, there are novelties, innovations and unintended consequences which create unstability. If social rule systems are stable, then this is the result of institutions and an extensive network of social controls. Burns and Flam (1987) offer an intriguing visualisation of "actor-system dynamics" which I reproduce here in a slightly adapted version.

Dynamics in social rule systems occur because the structural conditioning of social action and interaction is not determining. Reformulation and transformation of rule systems tend to occur when there is "socio-cultural incoherence" (e.g. when there are multiple contradictory rules systems which converge on concrete interaction settings), or when there is "functional incompatibility". The latter is the case when "social organization does not 'fit' the concrete action conditions, action processes, or technologies and resource dispositions obtaining in historically given situations. Under these conditions, actors are inclined to introduce rule innovations and, ultimately, to reform or transform the rule systems constituting social organization. (…)." (385). In general, reformulation and transformation of rule regimes and regime complexes tend to occur under conditions where: "power shifts and social control failures occur among established groups adhering to differing organizing principles and regimes; new social agents or coalitions — movements, classes, professions, parties or political elites — emerge, advocating new organizing principles and regimes and possessing sufficient social power to introduce these; the core technologies or resource base of established rule regimes are substantially altered." (386).

For my questions on emergence of cosmopolitan rules, Burns and Flam's (1987: 385-6) enumeration of situations in which functional (or system) incompatibility occurs is informative. For instance, if novelty is introduced, established rule systems tend to run into problems and induce rule system restructuring. "The introduction of substantially new technologies and innovations often contradicts the rules of established social structures. In this way, social agents — through innovations in technique and technology — change the conditions

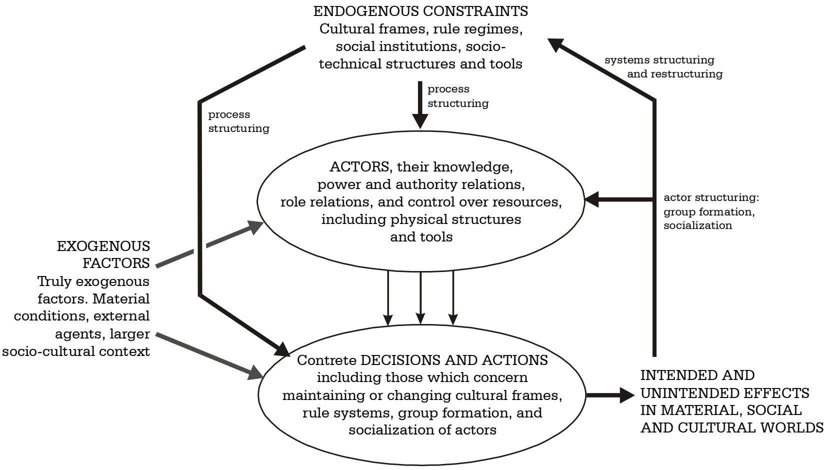

Figure 1.3 A general model of actor-system dynamics (adapted from Burns and Flam (1987: 4).

of their actions, often unintentionally. (Comprehending and regulating the very new or the unknown is highly problematic.)" (385). Social learning and innovation may also lead to shifts, as is exemplified in "the codification of laws and regulations, the systematization of sciences and mathematics, and the professionalization of occupations." (385). Unintended consequences and changes in environmental/physical conditions are also sources of alterations in rule systems. Reformulations and transformations are likely to involve "the emergence of new groups, social interactions, and resource control mechanisms which do not fit the initial assumptions and formal institutionalized relationships of established regimes." (386). A key element of social rule system theory is, is that transformations "never start from scratch" (383). In other words, when emergence of new rule systems, or regimes, is studied, one has to take into account existing structurations.

Important elements in social rule system theory are the emphasis on the fact that there is no simple causality, that changes should be understood as a multi-level phenomenon, and that not only social structures and institutions, but also material structures should be taken into account. Burns and Flam (1987) do not take up the issue of how translocality of technological knowledge is achieved.

Actor-centred institutionalism

The issue how institutions structure actions and interactions of actors is a central theme in actor-centred institutionalism (Schmidt and Werle, 1998). Some of its applications to technology are relevant for my questions. Characteristic of its applications to technology is the focus on institutions (as systems of rules that structure the courses of actions that a set of actors may choose), intermediary organisations (like standardisation organisations, industry associations, professional societies, research institutes and consulting engineering firms), and infrastructures of competence, skill and knowledge. In actor-centred institutionalism, technological choices are explained as outcomes of the actions and interactions of intentional actors which are channelled and framed by both technological artefacts and institutions. Frames entail both a knowledge facet (cf. technological paradigms) and an institutional facet.

Schmidt and Werle (1998) used actor-centred institutionalism to study committee-based standardisation. In this framework, outcomes of the standardisation processes are understood as resulting from the interaction of actor-related and institutional variables with case-specific technical factors. They showed how (international) standardisation organisations provided an institutional framework and a platform for discussions and negotiations between actors involved in standard-setting. They argue that without such an institutional framework, the collective good of standards may not be produced. "Even when all parties are willing to cooperate, the necessary rules may be missing, unknown or unavailable because of their character as a collective good; appropriate arenas for the establishment of these rules may likewise be absent." (5). While Schmidt and Werle do not explicitly address the issue of translocality, their foregrounding of institutional frameworks and (meso-level) intermediary actors is important.

Social network theory

Social network theory (Weyer *et al.*, 1997) foregrounds the emergence of structures — the mechanism of structure building — and thus is relevant for my questions. Weyer takes Coleman's (1990) disentanglement of structuration as a point of departure. Coleman distinguishes between three processes: how the structural level enables and constrains the behaviour on the actor level; how actors act and interact and influence each other; and how actions and interactions of individual actors add up to collective effects and changes at the structural level. The overall process can be depicted as a "boat" in which the stern is the down-arrow from structural to actor level; the keel is the ongoing behaviour of actors; and the bow is the up-arrow from actor to structural level. The arrow between both ends of the boat represents the transformation on the structural level. In other words, in order to understand structural changes one has to look at what happens "underwater" at the actor level. In my visualisation of Coleman's "boat" in Figure 1.4 I use Van de Poel's (1998) version which adds ongoing arrows which go up and down to indicate the duality of structure. (In terms of affordance structures, it indicates that initially there are affordances on a collective level which shape dynamics on the actor level. A co-evolution begins in which the affordance structure and the actor level mutually influence each other.)

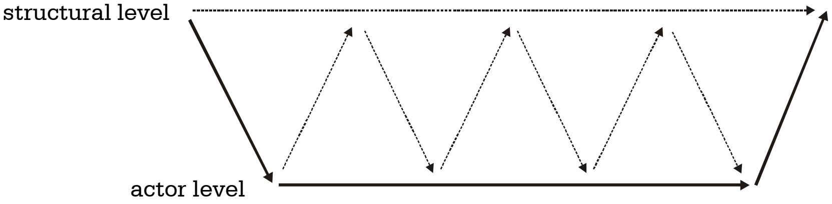

Figure 1.4 “Coleman’s boat” (Van de Poel, 1998: 27)

Focusing on the “problem of emergence”, Weyer argues that it is remarkable that the third arrow (from actor level to structural level) usually receives little attention. Weyer *et al.* (1997: 60-1) “vermuten, daβ eine Theorie sozialer Netzwerke beitragen kann, diese *Leerstelle in der soziologischen Theorie* zu füllen, die in den *Vernachlässigung des Emergenz-Problems* besteht.” The interaction type of social networks is capable of keeping the balance between process and structure.

> “Das Spezifikum des Interaktionstypus “Netzwerk” besteht daher in der Fähigkeit, die *Balance zwischen “Prozeβ“ und “Struktur”* zu halten, d.h. einerseits den Mechanismus der spontanen Selbstorganisation von Interaktion (und damit innovative Dynamik) nicht durch starre Regeln auβer Kraft zu setzen und andererseits die Potentiale alternativer Strukturen nich durch permanentes Chaos zu behindern (…). Soziale Netzwerke stehen also vor der — scheinbar paradoxen — Aufgabe, *Ordnung aus Unordnung* zu schaffen, ohne dabei die Unordnung zu zerstören.” (70; the quote is in German because it would be a pity to disturb the ordering that Weyer created in his text.)

Social networks emerge when reciprocal alignments occur between intentional actions of two or more actors, and when these constitute a self-reinforcing feedback mechanism which strengthens itself in a dynamic of its own. The process of structure building by self-organisation begins when actors succeed in mobilising other actors. When actor strategies become aligned, and a translation occurs which enables a durable exchange of resources, a social network can emerge. When alignments are sustained (because they are in the interest of all participants), the network can stabilise and get a dynamic of its own (Weyer *et al.*, 1997: 96-7).

In their application of social network theory to technology, Weyer *et al.* (1997) argue that the emergence of technology should be studied as a three-phased process: emergence; stabilisation; and perseverance (*Durchsetzung*). In different phases, technological developments are carried by different social networks in which actors with different motives and visions of utilisation act and interact. In the first phase, a “socio-technical core” is achieved which is a paradigmatic model that consists of two interrelated elements: a technical-instrumental configuration (in the form of a general operational principle (cf. Vincenti, 1990) and a social configuration (in the form of an anticipated arrangement of participating actors). “Der sozio-technische Kern stellt ein *allgemeines Orientierungsmuster für die Such- und Problemlösungsstrategien der Technikkonstruk-*

teure dar, das ihre konkreten Entscheidungen und Alternativwahlen beeinflußt, keinesfalls aber deterministisch festlegt." (38). Characteristic for the first phase is the involvement of (possibly amateurish) tinkerers. The stabilisation phase emerges through social "Vernetzung" of a broader range of actors. In this phase, the new technology is systematically explored and improved. The final perseverance phase emerges when the social network is again broadened with users and other stakeholders. In this phase, the technology becomes a context-free manageable technology which is no longer tied to its original context.

The relevance for my questions is that Weyer *et al.* (1997) explicitly focus on the emergence of structures — which is often neglected in social theory. They point out that new structures emerge through alignments and increasing interdependencies between (heterogeneous) actors (*Vernetzung*). Also their distinction between three phases is relevant, since it draws attention to the fact that technologies and technological knowledge are produced by heterogeneous actors in changing networks. Their discussion of decontextualisation of technology does not take into account the achievement of translocal knowledge explicitly, but my focus on translocality can be seen as a useful addition.

1.2.3 Neo-institutionalist theory

Typical questions for institutionalist theory are: Why do different localities resemble each other? Is behaviour shaped by conventions, rules and habits, or by personal interest? Why and how do laws, rules, and other types of regulative and normative systems arise? Do individuals voluntarily construct rule systems that then bind their own behaviour? Why do individual conform to institutions? Because of rewards, obligation, or lack of imagination? (Scott, 1995). Clearly, this theory is relevant for my questions about institutionalisation and cosmopolitanisation of technological knowledge. But neo-institutionalist theory is a broad label which covers economic, political science, as well as sociological versions of institutionalism.[23] Neo-institutionalist theory in economics provides relevant insights on the situations in which it would be efficient (on a collective level) to create rules and maintain institutions. Economists are interested in rule and governance systems which regulate or manage economic exchanges (and which may exist at multiple levels). The focus tends to be on the comparative efficacy with which alternative generic forms of governance — markets, networks/hybrids, hierarchies — economise on transaction costs, not on the broader questions of origins and changes in the institutional rules of the game. Economic theory is mostly interested in stabilised situations rather than in how they have become stable. Yet it is recognised that the achievement of institutions (as collective goods) tends to be difficult, and it is argued that incentives and institutional arrangements (e.g. trusted third parties, governmental intervention) usually are required. In general, in economist neo-institutionalism the

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[23] For a more detailed discussion on different strands in neo-institutionalist theory see Scott (1995).

constraining aspect of institutions is emphasised, rather than the enabling aspect (cf. the notion of institutions as repertoires). The duality of structures is not taken up. Such an approach to institutions will work only in situations which are more or less stabilised.

Another strand of neo-institutional economics, closely related to rational-choice approaches in political science and some schools in sociology sees institutions as edifices constructed by rational actors seeking to promote or protect their interests. Institutions are perceived as rational solutions to collective problems. An interesting example is Vining and Weimer's (1997) study of "saintly supervision" in the monitoring of casino gambling in British Columbia. They found "a rather unusual harnessing of nonprofit charitable organizations for the monitoring of revenues generated by gambling casinos" (615). Volunteers of charitable organisations (which received 50 percent of the net receipts of the casino to which they are assigned) ensured that money collected at tables was appropriately accounted for in total receipts and was not skimmed off by the casinos. They use this case study "as an illustration of how governance relations can be designed to take advantage of the incentives of particular third parties." (615).

The rational actor approach has been criticised in historical institutionalism (in economic as well as political science approaches in neo-institutionalist theory), to the extent that it tends to oversimplify institutionalisation processes. Historical reconstructions of institutions show that many structures and outcomes are not those planned or intended. Institutionalisation is a path dependent, multi-actor process; it is indeterminate and context dependent. Indeed, actors and structures mutually define each other and co-evolve (cf. structuration theory and social rule system theory). North (1990), for instance, in a historical study on the performance of nations, showed that a country like Spain was stuck in a pattern which was difficult to get out of. He concludes that methodical individualism needs to include actors which become entangled in structures and institutions which create constraints and path-dependencies (on the level of nations). A lesson from historical institutionalism is that one must be careful in using rational-actor type of explanations, in particular because rationality depends on actors knowing what their preferences are and being able to predict what the outcomes of their actions and interactions will be. This is not likely to be the case in emergent situations which I intend to study.

Ideational and cognitive aspects of institutions are foregrounded in sociological neo-institutionalist theory. Meanings do not just exist subjectively in the minds of people, but also objectively (as "social facts") in institutions. Institutions are perceived as complexes of rules that have been increasingly "rationalised" through the actions of professions, nation-states, and the mass media. The processes of objectification and rationalisation offer interesting clues for my questions, since they refer to processes whereby knowledge is made translocally available for local practices. How are objectivation and rationalisation achieved? In general, sociological versions of neo-institutionalism argue that meanings emerge and become shared in interactions. Meanings can achieve an "objective form" through processes of 'sedimentation' and 'crystallisation' which are the outcome of processes of typification of roles, ideas, actors, and events. Such insights in processes of typification, sedimentation and crystallisation can be transposed to processes of institutionalisation of technological knowledge provided the specific character of technological knowledge is taken into account.

DiMaggio and Powell (1983), when addressing the issue of isomorphism in organisational fields (which overlaps with the emergence of regimes), contend that there are three types of processes by which local practices are institutionalised: coercive, mimetic, and normative processes. Coercive isomorphism results from pressures exerted on organisations by other organisations upon which they are dependent and by cultural expectations within society. The legal environment is one source of coercive isomorphism. Mimetic isomorphism results from efforts of organisations to reduce uncertainties by modelling themselves on other (successful) organisations. The modelled organisation may be unaware of the modelling or may have no desire to be copied. Models may be diffused unintentionally, indirectly through employee transfer or turnover, or explicitly by organisations such as consulting firm or trade associations. Normative isomorphism stems form professionalisation. Organisational norms, which are created by actors like universities and professional training institutions, are adopted by professional managers. Elaborate social networks further diffuse these norms.

These mechanisms can be transposed to technological regimes: technological knowledge is institutionalised by coercion from regulators, dominant customers, or other dominant actors; by mimesis in the form of reverse engineering, or other forms of copying, whether or not stimulated by consultants or industry associations; and by norms as established by professional societies, industry associations, training institutes or other regulatory bodies. Implicit in these mechanisms is that translocality is somehow achieved — whether by making knowledge robust and translocal, by reducing variabilities between local contexts, or by both. Moreover, translocal (i.e. robust, mobile, institutionalised) technological knowledge, once achieved, can itself have coercive, mimetic and normative effects (cf. "paradigm"). The notions of 'rationalisation', 'objectification' and 'typification' already hint at such effects.

The relevance of neo-institutionalist theory, in particular the sociological strand, lies in the conceptualisation of how institutions enable and constrain actors. Especially the focus on how ideational and cognitive elements are objectified and rationalised as to become part of institutions, as well as the dynamics of isomorphism, are interesting for my questions. Also the attention which is paid to institutionalisation as an unintended outcome of path-dependent multi-actor processes is informative. Since neo-institutionalist theory ignores (or takes for granted) translocality of *technological* knowledge, my study on cosmopolitanisation might provide a valuable addition.

1.2.4 Figuration theory

Elements of Norbert Elias' (1978) figuration theory provide valuable insights in how collective outcomes are achieved. Like Giddens (who follows Merton), Elias argues that the outcome of the combination of human actions is most often unplanned and unintended. The task for sociologists is, then, to analyse and explain how unintended patterns of social life emerge.[24] Figuration theory is in some respects similar to structuration theory because it is argued that the behaviour of an actor can only be understood as part of a structure of mutually oriented and interdependent actors, i.e. a "figuration". Elias (1978) elaborates his figuration theory with a series of increasingly complex game models of "interweaving processes" (cf. *Vernetzung*, Weyer *et al.*, 1997) in which only some of the rules are pre-given. Such game situations have also been studied empirically, e.g. in social simulation studies (Wilhelm and Bolk, 1986; Van der Meer, 1983). In the course of such simulations rules and stable patterns indeed emerged.

The starting point is a simple game model with two players. If one player has more playing strength than the other, the winner not only has power over its opponent, but also a high degree of control over the game as such. Thus, the dominant player can, to a large extent, determine the game process and its outcome. If the opponent becomes stronger, the dominant player can no longer control the game. The individual moves of both players become dependent upon the game process. The game increasingly can be characterised as a social process, and decreasingly as the execution of an individual plan. The interweaving of the moves of both players results in a game process that none of the players intended.

When more players enter the game, different situations can emerge. If a dominant player plays separately with either one of the other players, he can still determine the outcome. But when the dominant player has to play with all of them at the same time, his chances to influence the game process depend on the extent to which the others cooperate and join forces. If the other players work together, thus gaining in playing strength, the outcome of the game can no longer be determined by either one of the players. The same holds if two groups of players emerge with marginal differences in playing strengths: no single player, nor any group can determine the game process and its outcome. In this model a "figuration order" emerges in which the actions (moves) of each party can only be explained as a link between the preceding figuration and the expected figuration of both parties.

An interesting point of Elias' figuration theory is that *multi-level* games may emerge out of multi-actor games. If the number of participants increases constantly, it becomes increasingly difficult for individual players to form an idea about the game process and of the changing game figuration. There are limita-

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[24] As a social theorist, Elias is interested in the interdependent, intentional and unintentional, relational, processual, and positional dimensions of social life. He argues against dualisms, such as structure versus agency, subjects versus objects, society versus individual, and macro versus micro (Elias, 1978).

tions to the size of the network of interdependencies in which individual players can still orient themselves and determine their personal game strategies. For individual players it is as though the figuration gets a life of its own. They will come to see that individual players are unable to see through or control the game. The game will become increasingly de-organised, which might induce players to re-organise themselves. This can work out in three ways. The group can disintegrate into many small groups, and these small groups can either become increasingly separated or form a new configuration of interdependent small groups that each play their own more or less autonomous separate games, while the groups still remain interrelated as rivals for certain desired goods. The third option is that the group of players remains integrated, but transforms into a figuration of a higher complexity with two levels.

Elias distinguishes between two two-level games (which can exist together): the oligarchical type and the democratisation type. In the oligarchical model, all players remain interdependent, but they do not play directly with each other. This function is taken over by special coordinating functionaries (e.g. representatives, delegates, leaders, governments, principalities, or monopolistic elites) which form a second, smaller group which operates on a second level. Players on the lower level play a minor role and remain nominal participants.

If the relative power of the higher level vis-à-vis the lower level decreases a democratisation model can emerge. This is the case when players at the lower level perceive players of the higher level as though they are there because of (and for) them. Higher-level players increasingly become functionaries, spokespersons and representatives of one or another group on the lower level. The strategy with regard to the (vertical) relation with groups on the lower level that each one represents, now becomes an aspect of their game which is equally important as the (horizontal) strategy vis-à-vis other players on the higher level. The whole figuration of these interwoven games branches off and become so complex that even the strongest talented player finds it difficult to make the right decision on its own. The game process which results from the interweaving of moves of a large number of players with reduced and decreasing differences in power, increasingly structures the moves of each individual player.

Players will come to perceive the game in a different way when they reflect on their game experiences, and they will develop impersonal concepts which take into account the relative autonomy of the game process vis-à-vis the motives of the individual players. Elias adds that this elaboration of concepts which reflects an understanding of the uncontrollable nature of the game process, is likely to be a slow and painstaking process because it will be difficult for individual players to understand that the uncontrollability of the game process, which they might experience as “suprapersonal”, actually is the result of their interdependency, their mutual reliance, and the tensions and conflict that are associated with their interrelatedness.

Elias' theory has been underpinned empirically by social simulation studies.[25] For instance, Wilhelm and Bolk (1986) set up a social simulation of Dutch sector councils (which are organisations for the programming of scientific research). These councils offer a forum for integration and coordination of research programming where scientists meet with 'users' of scientific knowledge and with government officials (primarily as sponsors of research). While enabled and constrained by the rudimentary world participants of the simulation find themselves in, they start to organise the structures, events and processes, i.e. act strategically. "They make use of situational 'cues' in the experimental setting on the one hand, and of former experiences on the other." (748). While interacting, the groups within the simulation develop characteristic activities, and figurations emerge. Depending on strategy, different stable figurations develop. Wilhelm and Bolk (1986: 757) conclude that "[i]t is the interplay of strategy and structure in figurations that determines the coordinates of the experienced world."

Games (or figurations) have been studied empirically also outside the field of social simulation. In political science, for instance, "games real actors play" (Scharpf, 1997) have been analysed. Examples are Mayntz and Scharpf (1975) who studied policy-making in West-Germany and Van der Meulen (1998) who studied national science policy making as principal-agent games, and found that institutionalisation of principal-agent relations can result in different stabilisations (or figurations), which differ to the extent the principal (the government) or the agents (scientists) can pursue their strategies. With such studies, Elias' notion about figurations emerging out of interaction patterns, can be empirically supported.

Elias' theory shows how increasingly complex figurations, which no one can control or manage, can emerge and stabilise. For my questions on the emergence of technological knowledge reservoirs in the context of emerging technological regimes, Elias' game models suggest that multi-actor situations can evolve into two-level situations, in which the level of local practices is increasingly dependent on outcomes of actions and interactions on a second, supralocal level. Thus, in cosmopolitanisation processes, a two-level dynamic may emerge, i.e. a division of labour between "local actors" and "cosmopolitan actors".

1.2.5 Actor-network theory

Actor-network theory (ANT) is a broad, ambitious and somewhat controversial theory.[26] Since it also addresses how actor-networks grow and stabilise and how "hot" situations can develop into "cold" situations, it is relevant for my pur-

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[25] In his PhD dissertation, Van der Meer (1983) developed a methodology of social simulation which was used to study figurations or games.

[26] Actor-network theory was developed by Bruno Latour, Michel Callon and others in the 1980s and 1990s. Like Giddens' structuration theory, it denies the agency-structure dichotomy.

poses. And, of course, because of the attention to the role of technological artefacts and other non-human actors. Many of its empirical studies could just as well be positioned as examples of evolving social or sociotechnical networks[27] (section 1.2.2), except that technical artefacts now play a structuring role as well.

The hyphen between actor and network indicates that actors and networks constitute each other — actors are determined by the networks in which they have been enrolled and translated. In ANT, the basic phenomenon is "criss-crossing mutual translations" (Rip and Groen, 2001: 15). Interactions are the basic elements, and actors are seen as "temporary assemblages of interactions" (15). Actions and interactions of actors introduce alignments, couplings, dependencies and anticipations. This happens not only in industrial networks, but also in "forceful repertoires" (20). Thus, also non-humans (e.g. elements of repertoires) are important as actors. Actors construct common definitions and meanings, define representatives, and co-opt each other in the pursuit of individual and collective objectives. Actor-networks consist of linkages in the form of circulating intermediaries, which can be written documents (scientific articles, reports, patents, etc.), people and their skills, money (e.g. contracts, loans, purchases), and technical objects (e.g. prototypes, machines, products). Actor-networks can grow by sending out intermediaries and enrolling/translating other actors. Circulation and mobility, therefore, are key elements of sociality.[28] Technological regimes can also be understood as actor-networks in which circulating translocal knowledge is an important element which constitutes, and keeps together, the actor-network. Van Lente (1993: 31) argues that ANT studies tend to terminate the analysis "as soon as a regularity or pattern is established." It is neglected that outcomes continue to exist and influence further interaction as they are "recognized by actors as being something that they should take into account" (31). In other words, a repertoire can emerge which actors continue to use.

Latour (1991) gives the example of an hotelkeeper who tries to get his guests to hand in the key at the reception when they leave the hotel. The hotelkeeper adds ever more elements to the key to ensure that guests return the key: an oral request, a sign to instruct the customers and, if these fail, a heavy weight that ensures that carrying the key is very uncomfortable. The "enroller" of these elements (in the example the hotelkeeper) must ensure that the enrolled elements act in the interests of the enroller rather than their own — which becomes increasingly difficult as the network grows. Latour analyses negotiations between different entities of a network as negotiations between a 'programme' and the response of an 'anti-programme'. Humans as well as non-humans are part of these negotiations/enrolments.

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[27] Concept of socio-technical networks was used by Elzen *et al.* (1996).

[28] Latour (1997) argues that "the social has this bizarre property not to be made of agency and structure at all, but to be a circulating entity."

While it will be clear that such interactions will occur all the time, to understand micro-interactions is probably not necessary to trace the overall pattern. What may be important is the insistence of ANT that humans and artefacts should not be treated differently. Or at least, that eventual outcomes are the result of co-evolution of interactions of human and non-human actors alike, whether as programme plus anti-programme or more broadly. In other words, one must be careful not to take features of technology as simply given and independent of actor strategies and actor constellations.

Of particular interest is Callon's (1998) distinction between "cold" and "hot" situations. In cold situations, identities, interests, preferences and responsibilities of actors have crystallised. A "regime of translation" has been established and interactions take place within the regime in expected ways. To understand the basic nature of such stabilisation, and its always partial character, Callon uses the concept of "frames" which create (temporary) boundaries around interactions, and bracket the rest of the world. Note that Callon uses the notion of frame not in the sense of a cognitive frame or mental model; frames create boundaries and bracket out the rest of the world. Frames are located in the situation, not in the minds of individuals. The notion of bracketing already indicates that "overflows" will occur, and these might destabilise regimes. When frames are unstable, or non-existent, then the situation is hot. It is unclear what the identities, interests, preferences and responsibilities of actors are. Whereas rational-actor explanations might be useful to explain actions and interactions in cold situations, in hot situations process-sociological explanations are required to understand the dynamics.[29] In order to understand how hot situations cool down, one has to study how frames are created and maintained. In technological domains, the production and circulation of translocal knowledge is a first step in the creation of a frame.

In chapter 2 I will further take up these issues in my conceptualisation of cosmopolitanisation. In the next section I will shift from general social theory to study how this phenomenon of hot situations being transformed in cold situations works out in industrial innovation. I will give an extended exposé of how this shift is conceptualised in theory of industrial dynamics.

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[29] Markets are possible in cold situations, thanks to framing work which has been done to make relations calculable. Individual agents which are clearly distinct and dissociated from one another, are established and defined by framing. Framing also allows for the definition of objects, goods and merchandise (Callon, 1998). Callon (2002) distinguishes more generally between emergent and consolidated configurations, and emphasises that "[t]he actor as described by methodological individualism, one who has acquired information before acting and who acts with perfect knowledge of certain impacts, cannot exist in emergent phases." (295).

1.2.6 Theory of industrial dynamics

In this section I will discuss studies in industrial dynamics which have foregrounded the shift from hot to cold situations. This resonates with general social theory which I discussed in previous sections, and it adds an element of time, i.e. patterns in which situations cool down. Garud (1994), for instance, following Tushman and Anderson's (1986) distinction between "eras of ferment" and "eras of incremental change", introduces a temporal frame in which he distinguishes between a "fluid" and a "specific" phase. In "industry life cycles", there tend to be sequences of fluid and specific phases. A "technological discontinuity" creates a fluid era of ferment which is ended by establishment of a dominant design, the beginning of a specific period of incremental change.[30] Technological discontinuities interrupt predictable, puzzle-solving patterns of technological evolution and initiate an era of ferment. During eras of ferment, dimensions of merit and their measurement become unclear which leads to increased technological uncertainty (and competition between rivalling designs). The emergence of a dominant design decreases technological uncertainty. Engineers direct their attention to refining existing products and processes during the subsequent era of incremental change. A fluid state is characterised by cooperation between complementary partners (e.g. user-supplier) and competition between rivals. A specific state, on the other hand, is characterised by competition within clusters and cooperation between rivals (who have adopted the dominant design).[31]

Tushman and Rosenkopf (1992) argue that social shaping of technology is paramount during eras of ferment. Social networks, communities and/or forums are likely to emerge which play a role in reducing technological uncertainties, and thus set the scene, and to some extent, prestructure the regime that will emerge. The emergence of a dominant design constrains technology, organisations, and networks during the era of incremental change. On the collective level, the establishment of a dominant design involves definition of critical problems, establishment of legitimate procedures, solving of technical puzzles, and emergence of community norms and values from interaction among interdependent actors (Van de Ven and Garud, 1989). Practitioner communities develop industry-wide procedures, traditions, and problem-solving modes that permit focused, incremental technical puzzle-solving. Relationships are solidified and elaborated within the confines of the dominant design. Technological activity is largely limited to information exchange and problem-solving within the dominant technological paradigm.

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[30] Tushman and Anderson (1986) used technological discontinuities and dominant designs as indicators to analyse differential patterns of firm entry, innovation, success, and exit.

[31] Dominant design literature appears to assume the need for a dominant design to emerge. But it is one possible outcome of socio-political struggle, and depends on socio-cognitive achievements.

This dichotomous view (ferment vs. incremental change; fluid vs. specific) is too simple to capture the complexities the phenomena. Van de Ven and Garud's (1989) framework for viewing an industry as a social system is helpful to identify mechanisms and dynamics in the transition from fluid to specific. They argue that it is necessary to take a broad definition of an industry, including institutions beyond the value chain. In particular, an industry infrastructure is included because "[m]any complementary innovations are usually required before a particular technology is suitable for commercial application [and c]ommercial success is in great measure a reflection of institutional innovations which embody the social, economic, and political infrastructure that any community needs to sustain its members."[32]

An accumulation theory of change is applied on the level of the motivations and activities of individual firms and entrepreneurs, and on the collective level of multiple actors who interact and socially construct an industry.[33] At the individual level, new industries begin with the purposeful intentions and business ideas of entrepreneurs. A totally new unit (be it a new technology, business venture, or programme) is created through a stream of activities undertaken by entrepreneurs to accumulate the external resources, competence, and ingredients necessary to transform and construct the business ideas into a self-sustaining economic enterprise. During the "initiation" phase entrepreneurs decide to form a business venture. During the subsequent "start-up" phase, the new unit must draw its resources, competences, and technology from the founding leaders and external sources in order to develop the proprietary products, create a market niche, and meet the institutional standards established to legitimate the new unit as an ongoing economic enterprise. During the "take-off" phase, the unit can exist without the external support of its initiators and continue growing "on it own". Thus, while change is stimulated by external forces during the initiation period, a transition from external to internal sources occurs during the start-up period, which culminates in the takeoff phase with the capability for immanent development.

At the collective level, "industry emergence represents the accumulative achievements of a new "community" of symbiotically-related firms and actors, who, through individual and collective action, invest resources in and transform a technological invention into a commercially viable business." (Van de Ven and Garud, 1989). During the "initiation" phase, paths of independent entrepreneurs (acting out of their own diverse intentions and ideas) intersect. These

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[32] The broad definition of an industry has similarities to a technological regime, although industry refers to production and sales, rather than technological knowledge production. Van de Ven and Garud (1989) use the example of cochlear implants. The commercialisation required the development of a totally new set of skills, knowledge, and institutional arrangements, including the development of new diagnostic and surgical procedures, service facilities, trained technicians, as well as the functional competences of R&D, manufacturing, and marketing. Commercialisation also required the creation of new industry practices and FDA regulations and standards of efficacy and safety of the devices.

[33] Van de Ven and Garud (1989) reject Darwinian evolutionary theories and punctuated equilibrium theory.

intersections provide occasions for interaction, and through such interactions the actors come to recognise areas of symbiotic (and commensalistic) interdependence. This recognition of symbiotic interdependence promotes cooperation because actors can achieve complementary benefits by integrating their functional specialisations. (Cf. *Vernetzung* (Weyer *et al.*, 1997). Out of these interactions there emerges a social system of organisational units that increasingly isolate themselves from traditional industries by virtue of their interdependencies, growing commitments to, and unique know-how of a new technology trajectory. This increasing isolation, which frees the new industry from institutional constraints of earlier industries and permits it to develop its own distinctive structural form, signifies the beginning of a start-up phase. There are two mechanisms for isolation: the accumulation of a critical mass of actors who believe that new technology can provide benefits that existing technologies can not provide; and the creation of new institutional forms and mechanisms.[34]

Using insights from neo-institutionalism on emergence of organisational fields (DiMaggio and Powell, 1983), Van de Ven and Garud argue that during the initial phase, *structuration* of an organisational field occurs as a result of the activities of a diverse set of organisations. This process of structuration consists of four parts: an increase in the extent of interaction among organisations in the field; the emergence of sharply defined interorganisational structures of domination and patterns of coalition; an increase in the information load with which organisations in a field must contend; and the development of a mutual awareness among participants in a set of organisations that they are involved in. Coordination among actors happens mostly through interactions and partisan mutual adjustments among actors, rather than by a central plan or organisational hierarchy, or through the price mechanism (if only because no products have been introduced in the market). “After all, environmental niches do not pre-exist, waiting to be filled; they are socially constructed domains through the opportunistic and collective efforts of interdependent actors in common pursuit of a technological innovation.” (Van de Ven and Garud, 1989).

During the start-up phase, price competition is largely absent, and technological competition emerges as alternative technological paths become evident and different entrepreneurs or firms “place their bets on” and pursue one or more of these alternatives. Risk-taking actors emerge which are willing to invest in R&D which is highly uncertain and dependent. Depending on the technological alternative chosen by a firm, technological development becomes highly dependent upon different clusters of institutions (universities, laboratories, disciplines) which have been producing and directing the accumulation of basic

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[34] In the case of cochlear implants, Van de Ven and Garud (1989) describe that as the number of believers increased, the number of activities (such as technical conferences and training programmes) that shared and promoted developments in new technology increased manifold, culminating in the endorsement of the new technology as a useful procedure by the American Medical Association. The FDA, for example, established a separate panel of evaluators and new terms and standards were introduced for evaluation.

knowledge, techniques, and experience associated with a given technological alternative.

As a critical mass of organisational units and actors has been gained, a complex network of cooperative and competitive relationships begins to accumulate. This network itself becomes recognised as a new "industrial sector", and takes on the form of a hierarchical, loosely-joined system. This emerging system consists of the key firms and actors that govern, integrate, and perform all of the functions required to transform a technological innovation into a viable line of products or services delivered to customers. When fully developed, this social system, which is embedded in social relationships that emerge from the interactions of the constituent actors, consists of subsystems, and each subsystem performs a limited range of specialised functions. Van de Ven and Garud distinguish between an institutional subsystem, a resource procurement subsystem, and an instrumental subsystem.[35]

Thus, there are many actors within and beyond the value chain which play an important role in the emergence of new industries. Firms, for instance, rely upon outside sources of knowledge and technical inventions, they rely upon financing arrangements, and on providers of a pool of competent human resources. This pool may develop when people which are recruited and trained by one firm join another firm, but also when industry conferences, technical committees, trade publications and technical journals emerge and provide opportunities for sharing and learning, and when informal networks emerge in which know-how can be traded.[36]

Clearly, industrial dynamics include a component of technological knowledge, even if it is not discussed explicitly. The literature on technological regimes focuses on this component (and neglects industrial dynamics).

1.2.7 Technological regimes

The notion of regimes refers to complexes of (more or less) shared rules on how to act and to interact, and to a system of corresponding interdependencies between (groups of) actors. Rip and Kemp (1998) define a technological regime as

> "the rule-set or grammar embedded in a complex of engineering practices, production technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems-all of them embedded in institutions and infrastructures."

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[35] The major functional activities of the institutional subsystem include provision of an industry governance structure; industry legitimation and support; and development of industry rules, regulations and standards. The functional activities of the resource procurement subsystem include basic scientific or technological research; financing, insurance, and venture capital; and human resources competence and accreditation. The functional activities of the instrumental subsystem centre around commercial product development by proprietary firms, vendors, and suppliers (Van de Ven and Garud, 1989).

[36] In section 2.3.2, Von Hippel's (1987) insights on informal knowledge trading between engineers are discussed.

A similar definition is given by Kemp, Schot and Hoogma (1998):

> "The whole complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructure that make up the totality of a technology. A technological regime is thus the technology-specific context of a technology which prestructures the kind of problem-solving activities that engineers are likely to do, a structure that both enables and constrains certain changes."

Implied in both definitions is that a significant part of technological knowledge is shared and institutionalised. In other words, part of the dynamics of regimes is the emergence of a collective knowledge reservoir. Also implied in these definitions is that divisions of labour are characteristic for technological regimes. Not only firms, but also governments and other regulatory bodies, sectoral laboratories, research institutes and universities, supplier and users may be part of a technological regime.

The question then is how technological regimes emerge. An example of a study of regime emergence is Van den Ende and Kemp's (1999) analysis of how a digital "computer regime" grew out of existing "computing regimes". They argue that the emergence of a computer regime was a process of transformation which can be conceptualised as a regime shift — i.e. a change in the rule set that underpins technical change, guiding innovative activity and output into particular directions.[37] Thus, the (new) digital computer regime did not start from scratch but started "from structures of the old regimes, and only later on developed its own distinctive elements." (833). The design and programming methods of the digital computer drew on specific changes in the existing computing regimes, particularly the increasing division of labour, the growing schematisation of computing activities and the development of more sophisticated punch card machinery. Van den Ende and Kemp (1999) do not explicitly address how translocality of technological knowledge was achieved.

Van de Poel (1998) provides the underlying theory of technological regimes and transformation processes. He notes that "[w]hat is crucial for the genesis of technological regimes is that actors at the local level interact and react to each other, creating interdependencies and so emergently a global level of artefacts, design tools, technical norms and the like which then enable and constrain further action at the local level." (Van de Poel, 1998: 13). This is similar to how Giddens described structuration processes. Socio-political processes of negotiation, coordination and technical agenda building play important roles in establishment and transformation technological regimes. At the same time, social shaping has its limitations, since in the end technological configurations have to work, and it may turn out that not all formulated requirements can be met.

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[37] Examples of such rules are technical standards, product standards, user requirements, design rules and organisational rules of how to produce, what to produce (Van den Ende and Kemp, 1999).

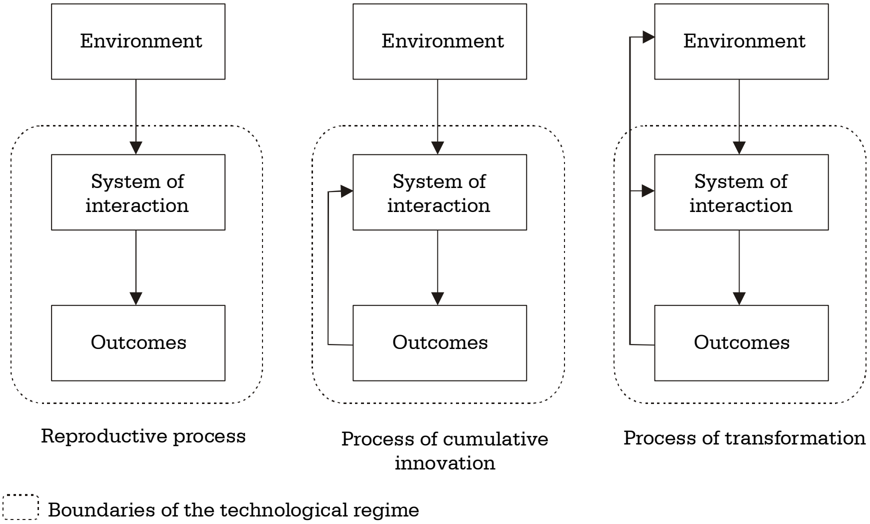

Figure 1.5 Three types of processes of social change distinguished by Boudon applied to technological developments (Van de Poel, 1998: 22)

To capture the multilevel dynamics, Van de Poel follows Coleman (1990) in his distinction between a structural level and the actor level. Van de Poel's version of "Coleman's boat" adds ongoing arrows which go up and down to indicate the duality of structure (see figure 1.4 in section 1.2.2). Outcomes on a collective level are shaped by interdependencies and role-relations between actors. To analyse transformations of regimes Van de Poel (1998) uses a sociological framework developed by Boudon (1981) to study mutual dependency and functional "systems of interaction".[38] This framework addresses the conditions under which systems of interactions reproduce themselves, innovate within the bounds of the system, or transform themselves.[39] Regime transformations occur when feedbacks from the environment start to affect the functional interaction system (see Figure 1.5). In eight case studies Van de Poel analyses such processes in detail.

This conceptualisation applies to situations in which there already is a

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[38] These systems of interaction are embedded in larger patterns, for example in so-called innovation patterns as first identified by Pavitt (1984). Van de Poel (1998) uses four innovation patterns to understand regime transformations. See further Chapter 2, section 2.3.3, actor-constellation affordances.

[39] There are similarities between Van de Poel's (1998) study of regime transformation in which he emphasises feedbacks of the environment, and Tushman and Anderson's (1986) emphasis on socio-political processes in eras of ferment. Van de Poel (1998: 26) adds that "feedbacks from the environment are not a sufficient condition for actual transformation of a regime. Other mechanisms and dynamics at the collective level are important as well."

technological regime. For situations in which new technological regimes do not succeed old regimes, or less clearly so, this conceptualisation has limitations. What remains is that, to the extent that cosmopolitanisation coincides with transformative periods, I should take feedbacks from the environment (or socio-political processes in a broad sense) into account in my conceptualisation.

Nelis (1998) presents an interesting analysis of the emergence of a technological regime in clinical genetics. She identified three overlapping phases: first 'circulation', followed by 'aggregation', and, finally, 'segregation'. Initially, novel knowledge is local, and available only in a small number of relatively isolated locations. Gradually, this knowledge begins to circulate, especially after an infrastructure for circulation emerges when exchange of materials, knowledge and people becomes an explicit goal of actors. Such an infrastructure enables regular and regulated circulation. In the case of clinical genetics, Nelis describes how in the 1970s, paediatricians who were confronted with the visible results of hereditary disorders, began to exchange experiences. They promoted the use of novel techniques such as chromosome analysis and prenatal diagnostics to identify congenital and hereditary disorders. In the subsequent phase of aggregation, novel knowledge accumulated in patients' and professional associations, specialist journals, and was transformed in norms and rules. Local practices were coordinated through circulation, and through coordination of articulation processes, a repertoire of rules emerges which could be shared by all the parties involved in their local practices. In the final phase of segregation, divisions of labour were established. Ethical committees, for instance, were made responsible for normative issues, doctors for clinical diagnosis, and civil servants for issuing licenses for DNA diagnostics.

In Nelis' (1998) analysis of regime emergence, coordination of articulation processes plays a key role. In case of novelty, articulation processes occur on multiple dimensions: articulation of technological options and specifications; articulation of demand and functional requirements; articulation of acceptability/admissibility; and articulation of a production and maintenance network. Gradually, articulation processes become coordinated through interactions and exchanges of actors and the emergence of an infrastructure. Interactions are structured by rules which are the result of these interactions. When outcomes of articulation processes and interaction patterns stabilise, and a division of labour has emerged, this signals the establishment of a (socio)technological regime.[40]

Thus, Nelis' account of regime formation concurs with insights from literatures discussed previously. The emergence of regimes is a phased process which involves the emergence of irreversibilities and divisions of labour as outcomes of interactions and interdependencies. In the 'segregation' phase, a reversal occurs and the regime with its rules is not so easy to change anymore. The epis-

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[40] Nelis (1998) emphasises that in her definition, technological regimes not only contain technological rules, but also economic, political, and social rules.

temic aspects of translocality are not taken up by Nelis explicitly, but she emphasises that emerging patterns of interactions play a key role in establishment of a collective repertoire.

1.2.8 In conclusion

My discussion of various bodies of literature might seem eclectic. To some extent this is true, since I did not choose one special theory but a range of theories which do not necessarily have a common underlying ontology. On the other hand, all the theories I discussed shared a similar perspective which foregrounded (multi-actor) processes, the duality of structure, and unintended consequences on a collective level. As Rip and Groen (2001: 13) argue, emergence of alignments and the build-up of patterns and structures, "is a general sociological phenomenon, and one which has been addressed in a variety of ways (…)".[41] In spite of different underlying ontologies, the overall picture "is reasonably coherent".

The review of relevant literatures yields some important insights. Following Giddens, cosmopolitanisation can be understood as a process of socio-cognitive structuration. Institutionalisation of technological knowledge can be analysed in terms of stretching of time-space and disembedding. Actors get engaged, involved, and build structures unintentionally, but they can also become reflexive. Structures can sediment in infrastructures and become a structural part of cosmopolitanisation. A two-level situation can emerge as an effect of increasingly complex interaction patterns (cf. *Vernetzung*). This means that cosmopolitanisation will involve the emergence of a translocal, cosmopolitan level of knowledge activities with a dynamic of its own. Technological knowledge production will become embedded in a local-cosmopolitan division of labour.

This can be visualised in a figure inspired by Rip's (unpublished) figure for local research and scientific fields. For technological fields, there will be differences and additional complexities. For instance, technological knowledge is a means to a practical end, and knowledge products must work in local contexts. In addition, knowledge producers are more heterogeneous as they include firms, research institutes, governmental agencies, technology users etc. Nevertheless, the basic idea remains the same: in technological regimes local practices are aligned to a field level and are mutually dependent. What I added in the figure is a third level, "landscape", which can capture background and long-term secular change.

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[41] Rip and Groen (2001) introduce the notion of "many invisible hands" to discuss the general sociological phenomenon in which interactions between actors get 'aligned' and build up to patterns and structures, which become relatively independent of the original interaction and will shape subsequent interaction. "Network structures, culturally embedded patterns and regimes, and strategic games enable and constrain like small invisible hands." (21).

1.3 Cosmopolitanisation and secular changes

Building on the summary visualisation in Figure 1.6, this section discusses secular changes in, and relevant to, cosmopolitanisation. As Disco *et al.* (1992) argued, cosmopolitanisation is part of a historical process of secular change. Very generally, it can be seen as an aspect of what Giddens (1991) discusses for modernisation as characterised by increased time-space distanciation. This is a cumulative process. Over the last centuries, the world has become filled with sedimented outcomes of cosmopolitanisation processes. These will offer a mould for further/other cosmopolitanisation. For example, and borrowing the term "technology infrastructures" from Tassey (1991), there are collectively available scientific, engineering, and technical knowledges "embodied in human, institutional, and facility forms" (Tassey, 1991). Nowadays, part of this infrastructure are intermediary actors such as research and test facilities, engineering firms, standardisation organisations, professional societies, and industrial associations. Over time, technology infrastructures have become denser and further articulated, but at each particular moment newly emerging technologies will be influenced by the infrastructures that are available. At the same time, they will contribute to those infrastructures. By now, such processes are recognised, and actors will anticipate on the emergence of cosmopolitan levels and act accordingly.

For my subsequent analysis of emerging technological regimes in the late nineteenth and twentieth century, I do not need a history of cosmopolitanisation of technology through the centuries, but it is instructive to indicate a few developments. If one goes back as far as the Renaissance, there were relatively few infrastructures. Nevertheless, translocal technological knowledge was produced and did circulate, as is illustrated by the practices of 'professors of secrets' (see section 1.1) and the existence of engineer's notebooks in which engineers accumulated and generalised their own experiences, as well as knowledge exchange with other engineers. Ferguson (1994), who notes this, also shows how engineering knowledge was made mobile using the technical device of technical drawings. Because it was pictorial and required few words to explain, this "knowledge was readily portable across cultural, linguistic, and temporal barriers" (Ferguson, 1994: 65). Master craftsmen, with their stocks of knowledge, circulated internationally in the Renaissance. Turnbull (1993) discusses in detail the cathedral builders in Medieval times. Circulation of experts was facilitated by patents which were employed "to encourage the introduction of foreign technologies through the immigration of skilled artisans from abroad. (…) It was hoped that the foreign master craftsmen would introduce (…) apprentices to the 'mysterie' of their respective arts. Since the master was not likely to remain in control of the newly skilled workers once they acquired journeyman's status, he obviously wished to be protected against the cohort of potential domestic competitors he would create." (David, 1993). Therefore he was given privileges and a monopoly of the trade. Among the courtiers at Renaissance courts were also scholars, artists, and engineers, and these formed "cosmopoli-

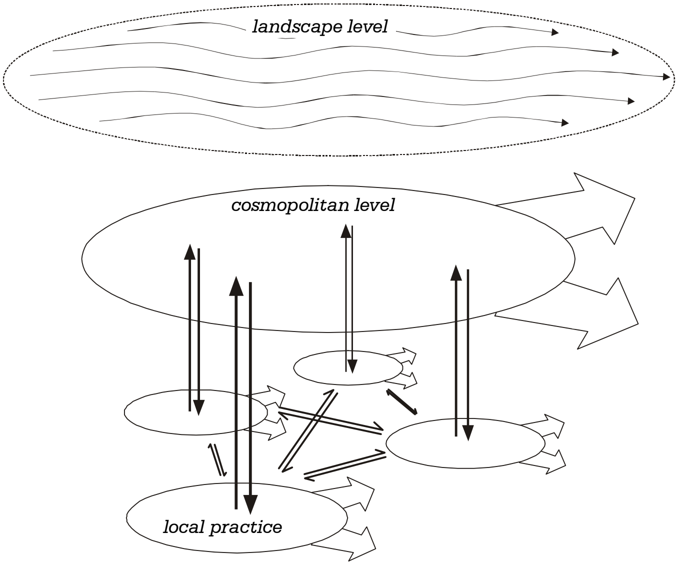

Figure 1.6 Local practices and a cosmopolitan level (with landscape level added).

tan nets" (as Biagioli (1993) called them) with competing colleagues at other courts. Such interlocal interactions stimulated the emergence of "virtual communities", linked through circulating texts and their contents (Rip, 2000b).

Ferguson (1994) recounts how from the fifteenth and sixteenth century onward traditions of illustrated printed books emerged. The first type of books was formed by (heavily illustrated) machine books called "theatres of machines" that suggested new and novel ideas. Renaissance engineers, "supported in their imaginative excursions by their royal and aristocratic patrons, were in fact happily compiling catalogues of material progress and technical possibilities" (120). In the tradition of machine books a "mechanical repertoire" was developed. In the nineteenth century classifications of the portrayed constructions were made at the École Polytechnique and at other places in Europe and America. These classifications resulted in numerous charts of "mechanical movements". These generic mechanical ideas played an important role in engineering schools. A further example is Pambour's 1839 theory of the steam engine which allowed calculations of design parameters and performance (without recourse to thermodynamics), and was intended for engineers as well as foremen (Kroes 1992: 74). Another type of books Ferguson discusses focussed on the recording of existing best practices. In the sixteenth century, for instance, books on the mining and refining of metals and other minerals were published. This tradition continued and widely visible examples with an added Enlightenment motivation were Diderot's Encyclopédie (1751-1780) and the Académie des Sciences' Description des Arts et Métiers (1761-1788). The interest in best practices was also visible in visits to other locations. During the Scottish Enlightenment, for instance, Scottish technologists travelled to the continent to gather technological knowledge.

How could such developments producing collective goods occur? At the individual level, it could be a matter of interest in learning and in spreading one's insights. In these brief examples one also sees the need to please sponsors (at the courts or otherwise), the philosopher's cause of the Enlightenment, and especially later, the interest of engineers in increasing their professional reputation.

In the eighteenth century, the first engineering schools were established in France, to be followed later by other countries. In the nineteenth century, engineers started to professionalise, and professional societies were established with their own engineering journals and conferences. Engineering societies and engineering schools became important actors in cosmopolitanisation of technological knowledge during the nineteenth century. Teachers in polytechnics began to develop abstract technical models in which the working of a class of technical configurations was described in a stylised manner, making artefacts become comprehensible as a system of interrelated and mutually constraining subelements (Disco *et al.*, 1992). Technical models became important means of knowledge production and dissemination, and became part of collective knowledge reservoirs within engineering communities.[42] Engineering schools and professional societies also became involved in meta-designing: the design of (theoretically sophisticated) design tools which could be applied in a range of local practices. Several technologies became increasingly academised and mathematised, and engineering sciences were developed.[43]

Engineering schools and recognition of professionalisation depended on the nation state which emerged as a strong actor during the eighteenth and especially nineteenth century. National governments took upon themselves the role of "system tending agencies" (especially in case of infrastructure systems) and developed expertise so that they could act as a "cosmopolitan tutor" to "localist contractors" (Disco, 1990). Nation states also became active in stimulating and facilitating (technical) education (cf. "school culture") and technology infrastructures (e.g. the establishment of the National Physical Laboratory in the

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[42] "Technical models start[ed] out as being socially embedded in local design practices, [and] eventually [became] embedded in a technical community, and (after a time) [were] formalized in engineering curricula." (Disco *et al.*, 1992: 472). In contemporary technological regimes, technical models often take the form of stabilised and objectively available cognitive and practical design heuristics.

[43] "Historically, the knowledge base and professional practices of engineers in many fields have changed appreciably as technology has become ever more scientized. In the past, engineering was often associated with practical craft skills and with the application of technical recipes to concrete problems. Since at least the second World War, the intellectual and professional gap that separated science and engineering has gradually diminished. Emblematic of the rapprochement is the increasing use of the terms "engineering science" in the Anglo-American world, "Ingenieurswissenschaften" in German-speaking countries and "science physique pour l'ingénieur" in France." (…) "The scientization of engineering is associated with growing cognitive specialization. New fields of academic learning have emerged, and many of them are directly relevant to engineering." (Joerges and Shinn, 2001).

United Kingdom and the Physikalische Reichsanstalt in Germany at the end of the nineteenth century).

In the nineteenth century, cosmopolitanisation of technological knowledge, and in particular the interest in facilitating cosmopolitanisation through different infrastructures, was part and parcel of the emergence of a bourgeois-professional-industrial society. In each particular case, there might well be cognitive, social and institutional thresholds to overcome in cosmopolitanisation, but the general idea and aspiration was accepted and carried by professional societies and other intermediaries.

During the twentieth century, development and application of technology became more knowledge-intensive, as is reflected for example by the emergence of systematic laboratory research whether in research centres or in industrial laboratories. Boersma (2002) has analysed the emergence of Philips Nat.Lab. as an invention in its own right, and drawn out the parallels with the laboratory of General Electric in the United States, and the laboratories of the big chemical companies in Germany. This allowed for "a division of innovative labour" (Arora and Gambardella 1994: 523), which then became recognised as such and led to attempts, of the nation state, often prodded by technologists, to facilitate and improve it. Recently, it has become fashionable to speak of national systems of innovation, and study their institutional structure (Lundvall, 1992; Nelson, 1993). Technological knowledge is widely recognised as an important source of competitiveness (and a key to strategic and military power). Innovation races, as for ever smaller integrated circuits or the mapping of genomes, create their specific mixes of knowledge sharing and secrecy.

In the secular changes leading to this brave new world, two further features have to be noted. Industrialisation as well as internationalisation of trade increasingly involved standardisation, which eventually also affected cosmopolitanisation. In the nineteenth century centralised production and economies of scale were achieved with (internal) standardisation. These standards referred to uniform products with regard to form, size and quality. In the mid-nineteenth century interoperability standards were developed (first in the United States) to ensure uniformity, replicability and interchangeability (Egyedi 1996). Especially in military domains interchangeability of components was important. This "armoury practice" was also applied in other civil domains, and was an input in the emergence of assembly line mass-production (Hounshell, 1984). These standards were inter-organisational agreements on measurements, symbols, signals, currency, product quality, etc. They provided an infrastructure and metrology for circulation of technological knowledge.

Since the mid-1920s standardisation came to play a more integral part in cosmopolitanisation processes when standardisation was employed as a means to create order, to achieve technical rationality and efficiency. It became important to establish what the "best practice" was, and to underpin this with engineering theory. As Shapiro (1997) emphasised, Codes of Practice in civil and structural engineering contain many rules based on accumulated experience of the industry concerning what is known to work. As he phrases it, standards of practice provide a means of mapping the universal onto the local. The International Organization for Standardization (ISO), accordingly, states that: "[s]tandards should be based on the consolidated results of science, technology and experience."[44] In the twentieth century, standardisation and technological developments have become closely interwoven. Indeed, as Antonelli (1994: 205) argues: "[t]he economics of standards and the economics of technological change seem in fact to be so intertwined that they cannot be separated."

Secondly, since cosmopolitanisation is about circulation of knowledge, developments in information, communication, and transportation technologies during the last centuries affected cosmopolitanisation, whether directly or indirectly e.g. through industrialisation and internationalisation. For example, the innovation of the printing press in the fifteenth century made it possible to circulate technological knowledge in written form on an unprecedented scale. Dissemination, exchange and accumulation of experiences, findings and ideas became much more easy. Enhanced capabilities for transportation and communication during the nineteenth and twentieth century stimulated wider diffusion of people, products and knowledge. Computers made it possible to make much more complex technical models, simulations and calculations. The Internet created new opportunities for interaction and communication — although the point remains that knowledge first has to be made translocal before it can be used effectively in other locations. Thus, information and communication technologies do not automatically lead to cosmopolitanisation.

Clearly, when studying cosmopolitanisation of knowledge in emerging technological regimes it will make a difference in which period of time these are located. When cosmopolitanisation is studied in case studies, the historically setting (historically evolved infrastructures, regimes, etc.) has to be taken into account. A further aspect, already visible in the above historical sketch, is reflexivity of the actors. Secular changes result in availability of infrastructure, and expectations about building them. Even though actors can be irreflexive about it, the overall evolution can still be called reflexive. Therefore, it is likely that actor strategies nowadays will be influenced by anticipations on cosmopolitanisation. As a result, they may try from the start to influence cosmopolitanisation processes, rather than to let cosmopolitanisation happen to them, i.e. evolve behind their backs. Moreover, cosmopolitanisation will never start from scratch, because there will be pre-existing mosaics of cosmopolitan levels and local-cosmopolitan divisions of labour. This is an important point when it comes to comparing across different cases of cosmopolitanisation.

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[44] ISO/IEC Guide 2: 1991 *General terms and their definitions concerning standardization and related activities.*

1.4 Road map for the thesis

In this introductory chapter I have presented the phenomenon of cosmopolitanisation, and I have embedded it in relevant literature. I have argued that it should be studied as a multi-level phenomenon and that an affordance-based understanding is the goal. I will further specify cosmopolitanisation and affordance structures in the next chapter. In chapter 3 I will briefly present the research design and the selection of case studies. The four case studies of reinforced concrete, paint, video tape/cassette recording, and air traffic control, are the subject of chapters 4 to 7. Chapter 4, on reinforced-concrete technology, can be read as a demonstration of the phenomenon of cosmopolitanisation. The next chapters build on those insights and further explore the role of different affordance structures. In the technological world of paint (chapter 5), cosmopolitanisation arrived much later, which is a contrast with reinforced concrete which calls for further analysis of similarities and differences.

It is to be expected that at higher levels in the technical hierarchy, more and more varied knowledge are relevant. Still, in the case of video recording (chapter 6), the process of competition, imitation and sharing is visible. For air traffic control (chapter 7), interoperability is a strong requirement: the same airplane must interact with different airports and airway controllers. In a sense, cosmopolitanisation should hang in the air — but in fact, the case study also shows the twists and vicissitudes.

After having presented the rich and varied patterns of cosmopolitanisation in these four cases, the concluding chapter will compare the results and evaluate them: in terms of what we have learned about cosmopolitanisation, as well as what these insights imply for current concerns about knowledge policy and knowledge management.

Chapter 2.

A conceptual model of cosmopolitanisation

2.1 Introduction

The aim of this chapter is to identify building blocks for a conceptual model, to be used heuristically when studying cosmopolitanisation processes in the context of emerging technological regimes. In chapter 1 I introduced my research questions: how can exchange and sharing of technological knowledge occur, and if it occurs, how can it be explained? I discussed relevant social theories (structuration theory, social rule system theory, social network theory, actor-centred institutionalist theory, neo-institutionalist theory, figuration theory, actor-network theory), as well as theories on industrial dynamics and technological regimes to provide a theoretical base under my questions. Relevant insights (in particular on emergence of structures) were that cosmopolitanisation can be understood as a process of socio-cognitive structuration in which cosmopolitan knowledge starts to orient local practices. Time-space distanciation and disembedding were central notions. Cosmopolitanisation is a multi-actor process in which a two-level dynamic can occur as a result of increasingly complex interaction patterns. It is likely to be a phased process in which a cosmopolitan level gets a dynamic of its own and begins to orient activities on a local level. In other words, the production and maintenance of a collective knowledge reservoir can be expected to be interwoven with the emergence of a local-cosmopolitan division of labour. I argued that an affordance-based explanation was needed to understand the complexities of cosmopolitanisation.

What about emerging technological regimes? Figure 2.1 is a way to capture the dynamics of such emerging regimes. It was originally used for other purposes, that is for conceptualising how novelty emerges in niches and eventually becomes embedded in transformed technological regimes and sociotechnical landscapes. But it offers an overall picture within which the process of cosmopolitanisation of technical knowledge can be embedded. In fact, the three levels sketched in Figure 2.1 are consistent with the types of levels in Figure 1.6.

My questions about cosmopolitanisation of technological knowledge are located in the lower left part of the scheme. The thin arrows going from the levels of landscape and regimes to the level of local practices indicate an initial affordance structure which orients actions and interactions of actors trying to develop a new technology. The figure indicates how a new technology starts

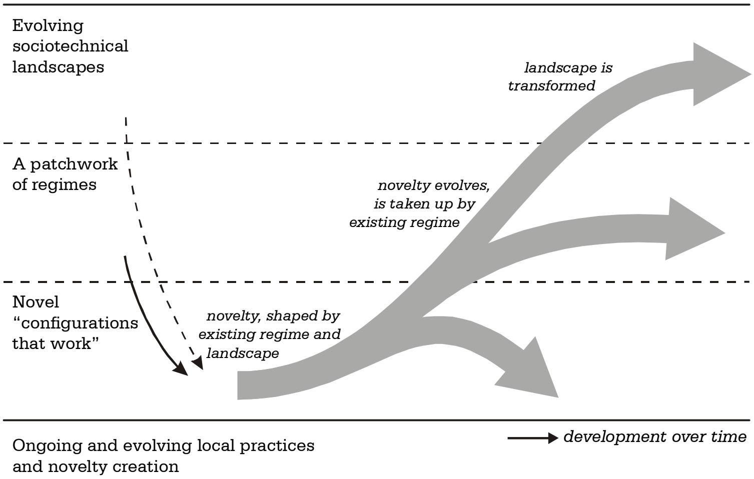

Figure 2.1 The dynamics of sociotechnical change at different levels, in which local practices, including those that involve novelty creation, occur in a context of regimes and sociotechnical landscapes, which exert influence on the shape and success of novel products (Kemp *et al.*, 2001: 277).

locally, in affordance structures which may not be supportive to the novelty and its promise. It takes time before it is recognised as a new and promising option. In these early phases, the novelty is still weak and thus depends on existing structures as affordances. As the novelty is taken up in ongoing interactions, the affordance structure will evolve, and technological characteristics and actor-constellations will crystallise out. It will be difficult to separate variables, until stabilisation occurs. The knowledge dynamics will be part of this evolution, and thus reflect these phases. But also drive the evolution, especially when articulation and sharing of knowledge allows a dominant design to emerge. Thus, my original formulation, cosmopolitanisation processes *in the context of* emerging technological regimes, is too simple. While this context will shape cosmopolitanisation processes, these processes and their outcomes will also shape the context. At some moment, this co-evolution stabilises, partly because of socio-cognitive processes where design heuristics and standards become authoritative, partly through institutional, political and market dynamics as in 'battles of standards' being decided by strategic alliances.

These observations indicate the outline of a conceptual model into which the various building blocks can be fitted. The model emphasises dynamic interactions and co-evolution which have to be reconstructed in order to understand what is happening. On the other hand, it is also important to try and explain features of cosmopolitanisation processes. To do so, one needs to reduce the complexity. The reduction of complexity which I will apply, and follow in the empirical case studies in the later chapters, is the scheme of dependent and (somewhat) independent variables. That is, cosmopolitanisation of technological knowledge in a domain, as predicated on and shaped by existing but then also co-evolving affordance structures.

Thus, this chapter consists of two parts. In the first part (section 2.2) I will specify my research object (or dependent variable, if one wants to use this terminology), the production of translocal knowledge and the emergence of a cosmopolitan level. For this, I will use additional literature, in particular sociology of (scientific) knowledge production. In the second part (section 2.3) I will specify the affordance structure which shapes cosmopolitanisation. I will argue that it consists of three (interrelated) aspects: technological characteristics, the nature of the actor constellation, and the historically contingent socio-technical setting (including existing mosaics of technological regimes and infrastructures of intermediary actors and forums).

2.2 On the production of translocal knowledge

In this section, I will specify my research object in two steps. First, in section 2.2.1, I address how cosmopolitanisation involves the achievement of translocal technological knowledge. Some studies in sociology of scientific knowledge where the question of translocality of knowledge is addressed explicitly are helpful for this purpose, because they focus on basic mechanisms which apply to the production of technological knowledge as well. In section 2.2.2 I discuss how cosmopolitanisation is bound up with the emergence of a cosmopolitan level of interactions which implies a local-cosmopolitan division of labour and an infrastructure for circulation of knowledge.

2.2.1 How translocality is achieved: insights from sociology of knowledge production

The existence of translocal technological knowledge which can be shared by a variety of local practices implies that knowledge has been made relatively context-independent and mobile. That "[u]niversality and context independence are not to be taken as given but must be analysed as precarious achievements" has been argued convincingly in sociological approaches to scientific and technoscientific knowledge production (MacKenzie and Spinardi, 1995: 44). Knowledge always starts as local and site-specific, and replication of knowledge outside its original context requires work. A key question for sociologists of scientific knowledge production is how scientists succeed in getting a particular solution developed in one laboratory (where the research is located), to work in another laboratory, and then getting it to work outside laboratories. Latour's well-known study of Pasteur's work on the micro-organism linked to anthrax in sheep shows the translations and mobilisations involved (Latour, 1983). In other words, the question of translocality is treated as a question of mobility. What does it take for knowledge to be able to move from one context to another without losing its value? Sociologists of scientific knowledge production set out to demystify the "universal" status of scientific knowledge by studying translocality as that what bridges localities through a productive combination of decontextualisation and recontextualisation — which itself requires a lot of tacit and local knowledge.

The importance of practical mastery of locally situated phenomena is combined with the challenge "how to standardise and generalise that achievement so that it is replicable in different local contexts. We must try to understand how scientists get from one local knowledge to another rather than from universal knowledge to its local instantiation" (Rouse, 1987, as quoted in Turnbull, 2000: 10). Thus, there is anticipation on decontextualisation and recontextualisation, and cosmopolitanisation is an explicit aim. Empirical studies of how knowledge is actually made to work in another context have shown how the production of translocality of knowledge requires epistemic as well as practical and social work.[1] For example, to determine what counts as successful replication, and thus as valid translocal knowledge, the scientific community has developed various rules to resolve the interpretative dilemmas of replication (Collins, 1985). Without them, translocality cannot be achieved.[2]

Turnbull (2000), basing himself on a number of intriguing case studies ranging from Medieval cathedral builders to advanced physics research on turbulence, argues that all knowledge production involves moving and "assembling" knowledge, i.e. the linking of various heterogeneous components, people, practices and places. Scientific knowledge production is a particular (and productive) mode of moving and assembling knowledge. Assemblage work is "the work of negotiation and judgement that each of the participants has to put in to create the equivalences and connections that produce order and meaning." (Turnbull, 2000: 13). 'Social strategies' and 'technical devices' play a key role in establishing equivalences and connections between otherwise heterogeneous and incompatible components, since they "provide for treating instances of knowledge/practice as similar or equivalent and for making connections, that is in enabling local knowledge/practices to move and to be assembled." (41). Various social strategies are possible, including standardisation and collective agreements about what counts as evidence. Technical devices may be material or conceptual, and include such items as maps, calendars, theories, books, lists, and systems of recursion. Their common function is "to enable otherwise incommensurable and isolated knowledges to move in space and time from the

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[1] Sociologists of scientific knowledge production have tended to emphasise the practical and social activities, rather than the epistemic activities, in order to demystify the status of scientific knowledge, but epistemic work remains important.

[2] There are further social and literary devices. The historians of science Shapin and Schaffer (1985) have shown how "virtual witnessing" was created (by Boyle) to overcome the fundamentally local and hence defeasible character of experimentally derived knowledge claims, and to enable knowledge to move out of the bounded private space of the laboratory into wider public space. Virtual witnessing required groups of reliable gentlemen witnesses, journals for carrying the "immutable mobiles" and technically reliable and reproducible experimental apparatus. In effect a new space was created in which empirical knowledge became credible and authoritative (Turnbull, 2000: 41).

local site and moment of their production." (44). The most successful devices are those which are mobile as well as immutable, presentable, readable and combinable with one another (Latour, 1987). Thus, to understand translocality, the methods, practices, instrumentations and technologies through which translocal knowledge is manifested have to be taken into account.

The result of the use of social strategies and technical devices, is "that which was previously completely indexical, having meaning only in the context of the site of production, and no means of moving beyond that site, is standardised and is made commensurable and re-presentable within [a] common framework" (Turnbull, 2000: 41).[3] In other words, translocality means that local knowledge gained at one site can be moved without too much distortion to another site. It then becomes possible to accumulate such mobilised local knowledges in "centres of calculation" for purposes of analysis, recombination and generalisation. This "aggregated localness" is a major source of scientific knowledge's robustness (184, quoting Leigh Star).

Hessenbruch (2000) presents an illustrative case study of how translocality was achieved in x-ray (radiology) technology through calibration and metrology networks. He juxtaposes three periods in the history of x-rays: the 1890s, 1900-18 and 1918-28, and charts the development "from extremely local cultures, with no sense of what might prove to be a useful calibration of x-rays, to a successful form of calibration, through which the 'salient features' of x-ray work lost their local colour. This development went from complete freedom to a strict circumscription of experimental interpretation. It also ended up with a highly disciplined labour process." (415). In the 1890s, when x-rays were discovered, "[p]ractitioners sometimes despaired of the x-ray tube" because it proved very difficult to get a particular result out of an experimental set-up, and to get that result consistently — let alone transfer their knowledge to other practitioners. Radiologists needed to know whether "what they are doing in one place and at one time, [was] the same as what they or someone else was doing at another place or another time, and if not to what extent it differ[ed]." (407). It was impossible to fully specify all of the experimental circumstances in terms of which the vagaries of x-ray production could be explained, and this led to a quest for salient features which amounted to finding appropriate calibrations. In turn, this induced efforts to theorise about variables contributing to its performance, i.e. to develop a technological model. "This kind of analytical work reduced the candidate variables to a handful" which facilitated knowledge exchanges, but also reduced "interpretative flexibility". The calibrations "acted as a set of guidelines with which work in one local culture could be received in another with some ease." (404). Eventually, "an infrastructure of disciplined, routine calibration [was developed which] centred upon authoritative institu-

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[3] Note that there are similarities with Giddens' (1984) discussion of disembedding and time-space distanciation (see section 1.2.1).

tions (in Germany, the Physikalisch-Technische Reichsanstalt; in Britain, the Post Office). Because of this infrastructure, practitioners had faith that these instruments were the same everywhere." (404-5). Thus, calibration helped to achieve translocality as it "allowed for intercomparison and statistical argumentation" (409).[4] In addition, it also reduced the risks for patients to get injured and the risk for radiologists to face malpractice suits. After the First World War, "the discipline was professionalized in the sense that independent lay radiological work was outlawed and, in Britain for example, a postgraduate radiology course was initiated." (410) This stimulated further institutionalisation of x-ray technology. In addition, a new recording device was developed. The Physikalisch-Technische Reichsanstalt, designed "an iontoquantimeter that was robust, in the sense that one could travel with it without changing its readings very much." (413). Interestingly, "loops of circulation" were required in which the instrument had to return to the original site regularly for calibration. What this case clearly shows, is how "technical devices" and "social strategies" underpinned the achievement of translocality.[5] Important elements in this achievement were a technical model, an infrastructure of calibration, an authoritative institution and professionalisation strategies.

Thus, the production of translocal knowledge depends on the achievement of mobility which allows for circulation, as well as accumulation and transformation of local knowledges (findings, experiences, etc.) into knowledge which is robust and transcends local contingencies.[6] Circulation and aggregation processes are not limited to scientific practices; they lie at the heart of efforts of all knowledge producers because they try to overcome variability across time and across place. These processes enable them to "learn from one place and time to another, and act [and build] on it with some confidence." (Rip, 2000a: 10-11). Figure 2.2 visualises the aggregation process. It can be further specified, e.g. for an engineering firm accumulating experience across projects and locations and checking and refining these insights into an aggregated knowledge repertoire available to members of the firm. I am interested in further, interorganisational, aggregation leading to the eventual production of translocal knowledge as a collective good.

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[4] Hessenbruch (2000: 404-5) adds that "[s]uch infrastructures were, of course, not peculiar to radiology. They were pioneered as means of achieving standard weights and measures, and were well established by the late 19th century. In the course of that century, similar infrastructures came into being for electrical measurements, and, for example, for batteries."

[5] A similar empirical illustration is presented by O'Connell (1993) who gives three examples of how "universality" — i.e. the "ability to bring facets of the world into the lab, and to move results achieved in the lab into the world" — is achieved by (expensive and labour-intensive) metrological practices.

[6] The issue of the quality of robustness of knowledge is not addressed by Turnbull (2000). There is no indication of what the deployment of social strategies and technical devices to move knowledge from its site of production to other places and times adds up to (Rip, 2002b).

Accumulation and transformation is not automatic, and dedicated effort is necessary to ensure that the knowledge is indeed reliable or robust. In fact, over the centuries three different modes of knowledge production have emerged in which circulation and aggregation processes are shaped differently and the grounds for accepting the knowledge as reliable are different (see Figure 2.3; Rip, 1997; 2002). The first mode of knowledge production is based on circulation of embodied knowledge and partial articulations and codifications between local practices. "This is the main mode of knowledge production in traditional knowledge, in the crafts, and in professional communities, also today, even when there is also strong input from other kinds of knowledge." (Rip, 2002a: 119). This mode of knowledge production has always been present and involves aggregation by learning by doing, learning by trying, as well as exchanging experiences and findings with other practitioners. Gradually, these experiences and interactions add up to more robust knowledge. This type of non-dedicated knowledge production is very common, but does not automatically add up to a cosmopolitan knowledge reservoir since there is no intentional strategy of making knowledge cosmopolitan, i.e. available on a collective level (which requires packaging). The need to continue with the job itself (rather than check the quality of what was learned) limits possibilities of systematic learning.[7]

The second mode of knowledge production involves a more organised and deliberate accumulation of local findings and experiences from different places and moments in a centre where they are compared, systematised, classified and transformed in more general and robust knowledge (cf. induction). This mode of knowledge production is typical for the tradition of natural history. "The key element is the attempt to recognize patterns which extend over time and place." (Rip, 2000a: 119). Examples of "summation points" are museums and staple markets. Also other intermediary actors, like standardisation organisations, professional societies, insurance companies, and classification societies (in shipbuilding) play similar roles in collecting experiences and findings in a central place in order to recognise patterns and generate translocal (standardised) knowledge. Nowadays, geographical information systems (GIS) are one example of how sophisticated collection, refinement and pattern recognition have become since the nineteenth century. This mode of knowledge production is also present in genomics.

A third mode of knowledge production involves controlled circumstances in a laboratory and in experimental situations more generally. In this mode

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[7] Argyris and Schön (1974) distinguished between single loop learning and double loop learning. In single loop learning actors learn to find better strategies to solve problems without questioning the underlying frameworks, assumptions, goals and values. The emphasis is on techniques and making techniques more efficient. Double-loop learning, in contrast, involves questioning the role of the framing and learning systems which underlie actual goals and strategies. Thus, double loop learning is more creative and reflexive. It is still "on line" but may involve reflexive try-outs and selection of what works. It can be added that such second-order learning-by-doing requires that try-outs do not involve too much risk. Aircraft pilots and air traffic control staff cannot try-out anything that comes into their heads.

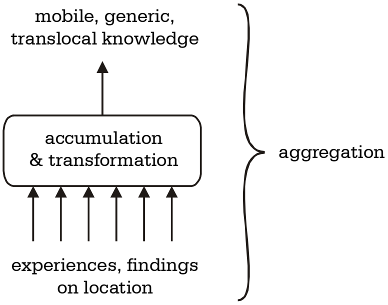

Figure 2.2 Aggregation

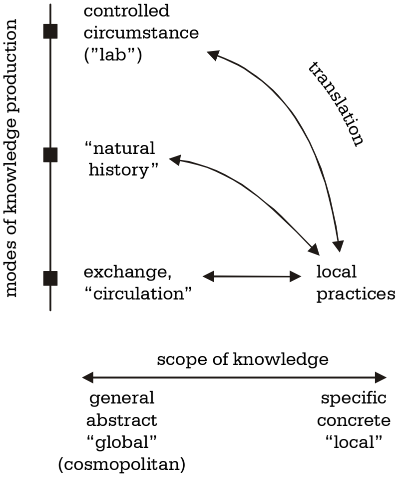

Figure 2.3 Modes of knowledge production (Rip, 1997)

variables can be changed in a controlled way, which allows for a systematic accumulation of deliberately created findings which can add up to robust knowledge. "The idea is that the phenomena created under such restricted circumstances allow access to background regularities which are valid more generally — at the very least as long as one can recreate the relevant circumstances." (119). The knowledge produced in this mode might be difficult to recontextualise in concrete local practices, which would require other skills and knowledge anyway.[8] Recontextualisation (and thus achievement of translocality) will be especially difficult if contexts are highly variable and difficult to discipline, e.g. in agriculture.

These three modes of knowledge production are similar to Pickstone's (2000) idealtypical way of describing "ways of knowing" (which are also ways of producing knowledge), which emerged (successively he claims) in Western science, technology and medicine. The first way of knowing was that of 'extracting

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[8] Collins (1985) has shown how reproduction (of a laser) in another laboratory was fraught with difficulties which could often only be resolved by visiting the original location and learning relevant skills. Rip (2000a: 120) adds that "the distance to "unrestricted" local practices increases from the first to the third mode of knowledge production. Translations and transformations between the knowledge claiming to transcend local practices and subsequent local practices to which these claims are to be applied are always necessary, but they require more effort going from the first to the second and then the third mode of knowledge production. On the other hand, if these efforts are successful, they can create impressive effects, as when Pasteur, in the late 19th century, demonstrated the power of his laboratory-based vaccine to protect sheep from anthrax — after carefully reconstructing the world outside the laboratory so that it would allow the emergence of this effect (Latour 1983, Latour 1984). In that sense, applying knowledge acquired in a laboratory to the wider world is a form of colonizing the world." (120).

meaning' or a hermeneutics of nature mode. Then came a natural history mode which involved collecting (in curiosity cabinets, museums, databases) and classifying. Classification enabled a next mode of analysis in which objects were broken up in their constituent parts. This allowed for a fourth mode of experimenting in laboratories under controlled circumstances in which new products and phenomena could be produced.[9] Pickstone emphasises that the several ways of knowing did not displace one another, and often different modes were combined. In addition, he situates his ideal types firmly within their institutional and cultural contexts: knowledge production and institutions co-evolved. For my conceptualisation, the historical succession of modes is less important than the classification of modes in idealtypes (which still exist today), although the historical dimension is illustrative for the influence of secular changes on cosmopolitanisation.

Taking translocality as that which can move between locations without great difficulty and as that which transcends local specificities, I can conclude that its production requires social strategies (alliances, trust, dominance) and technical devices ("immutable mobiles", metrology, standards, instruments), and that circulation and aggregation work are key elements in the production of robust, translocal knowledge. Although production of translocal technological knowledge has advantages in terms of reductions of uncertainties, complexities and costs, translocality is not an end in itself in technological fields.[10] Indeed, investments in research tend to be risky and often do not yield immediate results. Nevertheless, technical communities and shared technological knowledge reservoirs exist, and engineers have adopted modes of knowledge production, and institutional arrangements similar to those in scientific fields.

2.2.2 Translocal knowledge and the emergence of a cosmopolitan level

The question remains how the production of translocal technological knowledge becomes organised, and how it is institutionalised in divisions of labour and infrastructures, for example in technological regimes. To develop this part of the conceptual model, it is sufficient to take the twentieth-century situation as the starting point, and consider the earlier nineteenth-century situation as less articulated. Actually, of course, it is a co-evolution of technology and institutions, with ongoing secular changes (cf. section 1.3). In the case studies, such

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[9] The inventorying of natural objects, technical processes, and diseases (and many other things) came to prominence in the eighteenth century. This was followed by a period in which the analysis mode became dominant (e.g. in the new chemistry of Lavoisier and apparent also in the reduction of diseases to serial events and lesions, of physical processes to vector sums, of complex machines to simple mechanical processes, as well as in a generally summative view of societies and economies). In the mid-nineteenth century the experimentation mode came to prominence in which new effects could be produced under controlled circumstances.

[10] It can be added that there are also disadvantages in terms of spillovers, difficulties in appropriation, etc.

secular changes will be visible and taken into account. Here, I focus on the articulated situation.

The notion of an "epistemic community" (Holzner and Marx, 1979) offers an entrance point to specify how production of translocal knowledge is institutionalised. An epistemic community consists of (groups of) actors that have a common interest in certain knowledge, and have organised activities and institutions for maintenance and innovation of the knowledge reservoir. Such a community is structured around knowledge activities, such as knowledge production, knowledge structuring, knowledge storage, knowledge distribution, knowledge utilisation, and knowledge mandating (Dunn and Holzner, 1988). Epistemic communities are not limited to scientific domains, but have also emerged in technological domains. In fact, epistemic communities are a general phenomenon, which can be understood as a two-level figuration in knowledge producing communities (Elias, 1978; section 1.2.4). In epistemic communities there are various practices and institutions that enable the production and maintenance of collective knowledge reservoirs. Examples of knowledge activities are research, in its various guises, education and production of educational materials, courses, journals and books, conferences and workshops, standardisations and other articulations of best practices (Dunn and Holzner, 1988; discussed in Rip, 1997: 4).

What kind of actors might become active in a two-level division of labour within technological epistemic communities? There is a range of intermediary actors which might become involved in a two-level division of labour. Professional engineering societies are known to be active on the second level as they organise conferences, workshops and standardisation workgroups, and publish journals, proceedings, and standards.[11] Professional societies not only play an active role in the production of translocal knowledge, but also in making outcomes of such activities available (or even mandatory) for local practitioners. They offer reputational rewards for members who contribute to the collective knowledge reservoir. Other examples of intermediary actors active in technological epistemic communities are engineering consultants, sectoral research institutes, technical centres or experimental stations of industry associations, standardisation organisations, groups at universities, governmental agencies in sci-

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[11] Rip (1997: 7, after Disco *et al.,* 1990: 501) gives an example of the establishment of a professional society: "In 1847, in the Netherlands, a circular was sent around to parties presumably interested in the formation of a Dutch engineering association. It proclaimed that, with the existence of such an organization, "the discoveries, the observations, the experiments, the inventions and the designs of engineers no longer need remain locked up in their studies; they can be more openly dealt with, evaluated, and estimated as to their worth, and the illuminating rays of art can be converged as in one focus."" Rip adds: "The phase about inventions locked up in their studies echoes the way experimental philosophers in the 17th century, through the Royal Society and in other ways, struggled to exchange knowledge without losing one's claims to it. The black boxes in the keeping of the Royal Society "so as to better secure inventions to their authors" is one of the steps in the long and drawn-out process which led to present-day publication practices." (Rip, 1997: fn. 14).

ence and technology policy, industry consortia, R&D programme organisations, etc.

Engineering consultants are in an excellent position to accumulate experiences and findings because they work for different client organisations. Through interaction, such intermediaries gain more experience which they can use to refine and differentiate the services offered and methods used, to learn about new business opportunities, to upgrade track records, etc. Apparently, it is in their professional interest to systematise and learn from their experiences, *and* to disseminate their aggregation products in conferences, journals, and to participate in standardisation committees and other forums.[12] Sectoral technical centres or experimental stations which perform research and do tests for a range of client organisations may also play a role in cosmopolitanisation. They have a range of experiences with local products and problems, and they can aggregate these experiences. It can be in the interest of these intermediary actors to disseminate their aggregation products.

In their efforts to develop and disseminate standards, standardisation organisations and their committees also are engaged in the production of distribution of technological knowledge. A typical activity, for instance, is the development of theoretical models or simulations in which different proposals for standards can be evaluated systematically. Standardisation also occurs in industry consortia. Different forms of collaboration may emerge within industries which can involve inter-organisational knowledge exchange and aggregation. University groups may also become active in production of translocal knowledge, for example when they become involved in meta-design, creation of technological models, or in offering theoretical frameworks for knowledge production. During the twentieth century, governmental agencies have also become more actively involved in circulation and aggregation (e.g. through subsidising research, stimulating collaboration within an industry, or by contributing to a technology infrastructure).

These actors intermediate between different local practices, and also intermediate between local practices and collective knowledge reservoirs. They are producers as well as distributors of translocal knowledge. A technical community with intermediary actors is not pre-given but co-evolves with technology. Once intermediaries are present and continue, they can structure further knowledge activities, and become a pre-existing mould for further/other translocal knowledge production.

In general, a whole range of infrastructure elements may emerge offering sites or 'spaces' for interaction, exchange, circulation and aggregation. The

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[12] One can contrast this with the recent and fashionable interest in knowledge management. It aims to help management to create intra-organisational knowledge bases (rather than inter-organisational knowledge bases). However, these approaches tend to focus on making tacit knowledge explicit, and on persuasion of individuals to share their experiences with colleagues, rather than on making knowledge translocal. Thus, codification may occur, but knowledge can remain organisation-specific. The next step, to publish results in journals and conference proceedings, and to participate in committees is not part of knowledge management.

emergence of infrastructures is part of the cosmopolitanisation dynamics. Once an infrastructure of such spaces used as forums is present, it may induce (local or intermediary) actors to participate in such forums, e.g. for reputational rewards, and it can structure further/other knowledge activities.

Recently, national innovation systems (NIS) have become a topic for analysts and for policy makers (Lundvall, 1992; Nelson, 1993). National innovation systems have emerged in the twentieth century and now provide a further context for contemporary cosmopolitanisation processes. While the literature on innovation systems tends to focus on institutions, one can find indications of how collective knowledge reservoirs are produced, maintained and accessed. There are a few studies on knowledge flows and how they are institutionalised which are particularly relevant, even though they focus on stabilised rather than emergent situations. Knowledge flows in a national innovation system have been studied by Den Hertog *et al.* (1995). They argue that institutional infrastructures are important for the flow of knowledge.[13] Such institutional infrastructures include "intermediary organisations between technology suppliers and users; intermediary organisations between firms or groups of firms for exchange of innovation experiences (technological, managerial) and collective action; public support activities for diffusion (support programmes/centres for application of technologies, for technology transfer, tacit knowledge flows, demonstration activities); the system of vocational education where tacit knowledge between firms and education institutes is exchanged." Examples of intermediary actors include technology brokers, technology transfer centres, consultants, (semi-)public bodies such as the Dutch Innovation Centres, and industrial research centres.

In the public part of the institutional infrastructure, higher education institutes and research and technology organisations are important. Higher education institutes not only produce graduates who start working in industry and transfer knowledge and technological know-how, but they are also (and increasingly) involved in performing contract R&D and contract training directly for industry. Research and technology organisations may act as institutions aimed at creating (specialised) basic knowledge, while others are engaged in translating and transferring the available knowledge and technical expertise into practical products and services for certain group of users. They may be active in a broad field of disciplines and industries or be more specialised at certain sectors or type of knowledge. Research and technology organisations can also have a role

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[13] Den Hertog *et al.* (1995) argue with regard to "distribution power" both transfer capacity and absorptive capacity are key notions. They note that there is an appropriation problem with regard to the transfer capacity. Alongside the spread of innovation efforts of intermediary actors in order to reap the economic benefits, there has to be protection of their knowledge. Cf. David (1993) on patents and journeymen.

in (further) education of R&D-personnel and therefore can develop into a pool of expertise.[14]

"Bridging institutions" (Bessant and Rush, 1995) stimulate the process of diffusion and technology transfer. [15] Examples include innovation centres, regional development agencies, (engineering) consultants, and patent agencies. An important category of bridging institutions are "knowledge intensive business services" (KIBS) which are defined as "private companies or organisations relying heavily on professional knowledge, i.e. knowledge or expertise related to a specific (technical) discipline or (technical) functional domain, supplying intermediate products and services that are knowledge based." (Den Hertog, 2000). Especially KIBS that derive their intermediate function primarily from the production and transfer of technology-related knowledge are relevant for my questions.[16] "One important role for KIBS is providing a point of fusion between more general scientific and technological information, dispersed in the economy, and the more local requirements and problems of their clients. KIBS operate as catalysts which promote a fusion of generic and quasi-generic knowledge, and the more tacit knowledge, located within the daily practices of the firms and sectors they service." (Den Hertog, 2000: 505).

There are different types of intermediary activities: expert consulting (providing solutions to particular problems); experience sharing (transferring what is learned in one context to another); brokering (putting different sources and users in contact across a wide range of services and resources); diagnosis and problem clarification (helping users to articulate and define the particular needs in innovation); benchmarking (where the process of identifying and focussing on "good practices" can be established through an intermediary); and change agency (where organisational development can be undertaken with help from a neutral outside perspective) (Den Hertog, 2000). Intermediary organisations can also contribute to production of translocal knowledge by providing a mechanism for collective production of knowledge. Associations and societies of various types, for instance, offer such a mechanism for collective action (e.g. pre-competitive R&D collaboration).

It is clear that elaborate divisions of labour and infrastructures have emerged by now, which will shape what is happening in specific technological

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[14] Den Hertog *et al.* (1995) conclude that through high levels of mobility of well qualified and experienced graduates from research and technology organisations to industry, high levels of good quality contract research, scientific and technological knowledge and expertise is further disseminated and distribution power increased.

[15] Bessant and Rush (1995) describe a wide variety of 'bridge building' consultancies and their contributions to technology transfer. They conclude that their role is no longer a linear one of passing information from suppliers to users, but "a flexible resource capable of filling the interstices within the overall innovation system."

[16] Den Hertog (2000) adds that the KIBS which are engaged in technological knowledge production and dissemination are often neglected in literature on innovation systems.

domains. Analytically, the interesting point is that a two-level situation obtains a local level at which actors try to solve their specific, local problems in their attempts to make configurations that work (and can be marketed), and a supralocal cosmopolitan level at which a variety of actors are involved in production and circulation of translocal knowledge, that is, technological knowledge which can be applied across a range of locations. Obviously, actors may be active on both levels. For instance, when an engineer who is employed by a company goes to a conference to present a paper, or when (s)he participates in a working group of a professional society.[17]

Cosmopolitan level activities centre around technological knowledge which is not tied up to the specifics of local problems, but at more general and generic knowledge. Stankiewicz (1992), in his discussion of socio-cognitive technological systems guiding technological developments, actually describes such activities and the agendas that are followed. [18] "In order to be retrievable, transmittable and operationally accessible the unwieldy corpus of technical knowledge has to be structured and whenever possible reduced to generic formulas. This creates an internal meta-technological research agenda based on the reflection on the "state-of-the-art" rather than determined by specific practical needs of the moment. It also leads to the separation of roles of the engineer (oriented towards the more or less creative application of the existing technical know-how to specific problems arising within concrete technical systems) and the technologist (seeking to extend the limits of technological capability by developing solutions to classes of problems)." Meta-technological research agendas focus on (1) the transformation of the application- or subject-oriented knowledge into generic principles and models, that is generalisation; and (2) systematic elucidation of the relationship between structure and function, i.e. development and articulation of "functional insight". This increasingly self-referential character of technological activity leads to the articulation of fundamental concepts and approaches which are then increasingly used in diagnosing and defining the "practical problems".

In stabilised fields, the cosmopolitan level provides guidance to local practices (by offering technological knowledge which can be applied throughout the field), and it also constrains local practices by offering standards, norms, and regulations on how to design and develop technical configurations. A cosmopolitan level can also reduce risks and uncertainties "by pooling local experiences, deliberating on the implications of such experiences for the management

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[17] Professional engineers are known to have such a double identity: loyalty to their employer but also to their professional community. (See, for instance, Graham (1986) in her study of RCA).

[18] A socio-cognitive technological system is defined as a complex of activities centred on the production, assembly and organisation of technological knowledge. Elements of such a system are scientists and engineers, educational institutions, R&D departments, research organisations, patent offices, professional and scientific associations, technical journals, as well as a knowledge reservoir containing symbolically coded, stored and communicated knowledge at various levels of generality and organisation. For socio-cognitive systems to exist, communication and interaction networks are crucial (Stankiewicz, 1992).

of technologies, and ultimately by formulating collectively sanctioned modelling procedures and practical algorithms, sometimes in the form of codified and procedural rules.” (Disco, 1990: 269).

How a cosmopolitan level emerges, and if patterns can be identified, is a question which has to be answered empirically. It should be emphasised that translocal structures emerge together with new technologies (i.e. co-evolution), but also continue and become a pre-existing mould for other/further translocal work. For example, once professional societies or consulting engineering firms exist, they will try to get involved in new technological developments. Another example is the collaboration between actors. When, in the early 1990s, the European Union introduced the collaboration between firms, universities and public laboratories in its Third Framework Programme (in particular in the ESPRIT Programme), there was some reluctance to participate. This did happen, however, and participants learned the advantages of working as a collaboration. Now, public-private collaborations are an integral part, not just of European Union Framework Programmes, but in many national government-supported research programmes (Rip, 1990).

I can now specify the sociocognitive dynamics in which collective knowledge reservoirs are created as a process of cosmopolitanisation which involves (a) the production of translocal knowledge (circulation & aggregation work); (b) the emergence of an infrastructure which supports and carries circulation and aggregation of technological knowledge, and (c) the emergence of a local-cosmopolitan division of labour in which various types of intermediary actors may play a role. Different patterns and differences in degree of cosmopolitanisation can be expected. The question is, can such patterns be identified and understood, while taking into account secular changes?

2.3 Understanding the emergence of cosmopolitanisation

How is it possible that cosmopolitanisation occurs, if translocality is to be achieved by the collective work of knowledge producers and cosmopolitan knowledge has the characteristics of a collective good? To develop a perspective I will first discuss, in section 2.3.1, insights from theories on the production of collective goods, and in section 2.3.2, lessons that can be drawn from economic theories on codification and knowledge sharing. In section 2.3.3, I will expand on the affordance structures for cosmopolitanisation. This completes the exploration of my conceptual model.

2.3.1 On the production of collective goods

Cosmopolitan knowledge has characteristics of a collective good, because it is non-rival and non-exclusive (for actors with adequate absorptive capacity). Non-rival means that the use of a collective good does not diminish its availability for others. Non-exclusive means that it is available for anyone, whether or not an actor has contributed to its production. Not only translocal knowledge has characteristics of a collective good, but the infrastructure and institutions for circulation and aggregation may be collective goods as well.

While the problem of collective goods as I intend to study it, cannot be understood with a simple rational-actor model, particularly not in case of emergent or fluid situations, the structure of the situation can be brought out by such an analysis. Mancur Olson Jr.'s *The logic of collective action: public goods and the theory of groups* (1965) is a pioneering work in the study of collective goods. His main questions are how collective action is made possible and what the influence of group size is. Before Olson wrote his book, it was widely accepted that it followed logically from the premise of rational, self-interested behaviour that groups tend to act in support of their group interests. Olson challenged this idea that individuals with common interests would voluntary act so as to try to further those interests. Instead, he argued that the possibility of a benefit for a group was insufficient to generate collective action to achieve that benefit. "Unless the number of individuals is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, *rational, self-interested individuals will not act to achieve their common or group interests.*" (Olson, 1965: 2). An actor who cannot be excluded from obtaining the benefits of a collective good once it is produced, has little incentive to contribute voluntarily to the provision of that good. Thus, there is a free-rider problem. If an actor cannot be excluded from the benefits that others provide, each actor is motivated not to contribute to the joint effort, but to free-ride on the efforts of others. If all participants choose to free-ride, the collective good will not be produced, and all will end up where no one wanted to be. Alternatively, some may provide while other free-ride, leading to less than the optimal level of provision of the collective benefit. When, in practice, collective goods are achieved, this is possible to the extent that collective action is accompanied by private incentives to reward contributors (e.g. in the form of membership advantages) or to punish non-contributors. Olson did not take into account that selective incentives also involve (some) costs (Ostrom, 1990). Indeed, paying for selective incentives is also a collective action because it will provide a benefit to everyone interested in the collective good, not just to the people who pay for incentives. Moreover, empirical studies which have been performed since Olson published his book, suggest that private incentives have a smaller effect than it is indicated by his theory (Ostrom, 1990).

In Olson's theory size and constellation (heterogeneity) of groups affect the degree of difficulty in the production of collective goods. The larger the group, the more difficult the production of collective goods tends to be. The more homogeneous (with regard to the size of actors) the group is, the stronger a tendency towards suboptimal provision of collective goods. Olson argued that a collective good will be provided at the level that the "largest" actor (for whom the personal gain is the largest) is willing and able to pay for, and once this largest actor has obtained the amount it wants, the other actors have no incentive to provide any more of the collective good. The larger the group, the smaller the capacity of one actor to cover the costs, and therefore the larger the suboptimality will be. If the size of the group exceeds a given threshold, no member, no matter how large, will be able to provide any quantity of the collective good.

Olson has been criticised for not taking into account the possibility of coordinating actions. The presumption is that for individual actors the behaviour of others does not have any effect on their own contributions. All an individual actor knows (and needs to know) are the total cost of providing the collective good, and the personal benefit derived from the public good. Individual actor are not aware of, and not concerned about, the possible existence of others interested in the same good. In practice, this is usually not the case.[19] For instance, as groups grow, it may become more interesting to join groups.

Thus, it can be concluded that, especially in the case of fluid situations, a theory of collective goods should take into account opportunities for interactions between actors and the emergence of groups. In other words, the theory of collective goods should become more sociological. While in Olson's model individual actors have only two options (i.e. provide the collective good themselves or do nothing), in reality they have more than these two options as they can also take an initiative of organising a group and gathering resources. This would be a far less costly strategy than to provide the collective good themselves. Also the presence of external actors and institutions can affect the production of collective goods. Governments, for instance, may develop policies to stimulate actors to contribute to the creation of collective goods. Policy options include subsidies, direct governmental production, and publicly regulated private monopoly (patent rights) (David, 1993). Also the presence of trusted third parties may enable collective action. "All efforts to organize collective action," Ostrom (1990: 28) argues, "whether by an external ruler, an entrepreneur, or a set of principles who wish to gain collective benefits, must address a common set of problems. These have to do with coping with free-riding, solving commitment problems, arranging for the supply of new institutions, and monitoring individual compliance with sets of rules."[20]

Furthermore, I want to emphasise that participating in, or contributing to, the production of a collective good may be rewarding for other reasons than the achievement of the collective good itself. For instance, participating on the cosmopolitan level may have benefits for actors because they can influence outcomes (e.g. standards), but also because it may offer opportunities for inter-

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[19] "People join groups involved in collective pursuits not only out of perceived common interests, but also because they regard the groups or individuals organizing the action as in some sense efficacious. (…) For most people, however, the most prominent and convincing evidence of a group's efficacy is probably the group's size and command over resources. (…) In this simple fashion, the decision of individuals who come into contact with a group or its organizer are clearly interdependent with the decision of others" (Marwell and Oliver, 1993: 10).

[20] In her summary of recent studies on the production of collective goods, Ostrom (1990) recounts that one or more of the following variables are consistently shown to influence outcomes: the total number of decision makers; the number of participants minimally necessary to achieve the collective benefit; the discount rate in use, similarities of interests; and the presence of participants with substantial leadership or other assets.

action and (informal) exchange, to gather intelligence, to create visibility for themselves, and to gain a reputation.

I already mentioned that non-exclusiveness of cosmopolitan knowledge is incomplete, because actors should have sufficient absorptive capacity in order to use cosmopolitan knowledge. In other words, actors have to invest in knowledge production (e.g. research) themselves in order to be able to "relocalise" translocalised knowledge. In addition, access to cosmopolitan knowledge reservoirs not only implies access in terms of expertise, "but also access to the informal, cultural, knowledge structuring elements of the reservoir, where a major part of the added value lies." (Rip, 1997: 19). A potential "accessor" might first have to indicate (s)he qualifies as a member of a cosmopolitan community. "Without an actual or potential contribution to the research area, one does not count as a member (…)." (19).[21] Thus, the problem of free-riding might be less than in cases of pure collective goods.

Lessons to be learnt from this discussion of public goods for my questions on cosmopolitanisation are that translocal knowledge will not be produced automatically even if actors perceive a (common) interest in achieving it. In order to understand cosmopolitanisation, I have to take into account the (heterogeneity of the) actor constellation, presence (and emergence) of governmental agencies and third parties (e.g. intermediary actors like standardisation organisations and industry associations), institutional arrangements and infrastructures, and (private) incentive structures that reward contributors and punish non-contributors. In addition, also (conditions for) interactions and coordinations between actors should be taken into account. Production of the collective good of cosmopolitan knowledge may well be a multi-stage process, in which actors first start to organise themselves and create incentive structures and means of coordination or collaboration, and then begin to invest in circulation and aggregation work. The emergence of forums and intermediary actors (i.e. infrastructures) will be part of the dynamics.

2.3.2 Codification and knowledge sharing

When economists analyse production and sharing of technological knowledge, they often make a distinction between tacit and codified knowledge. Cowan and Foray (1997) describe codification process as follows:

> "Typically, a piece of knowledge initially appears as purely tacit — a person has an idea. Often, though, as the new knowledge ages, it goes through a process whereby it becomes more codified. As it is explored, used and better understood, less of it remains idiosyncratic to a person or few people, and more of it is transformed into some systematic form that can be communicated at low cost. In some cases, as the principles underlying the piece of knowledge come to be understood, they can be written down, and

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[21] "Without such an active contribution, one can still access members and profit from their knowledge and experience, if one can show to be knowledgeable" (Rip, 1997: 19).

> the piece of information can be described as an instantiation, under certain initial conditions, of a general phenomenon. In other cases, a procedure becomes routenized and repeatable, which implies that it can be broken down into component pieces, each of which is sufficiently simple that it can be described verbally or embodied in a machine. This, again, is a process by which tacit knowledge becomes codified."

Clearly, codification has overlaps with cosmopolitanisation. Therefore, insights on codification can contribute to an understanding of cosmopolitanisation. Codification of knowledge is an important issue because it reduces the marginal costs of knowledge transfer, storage, combination, verification, etc. substantially (after high fixed costs have been borne). Thus, codification changes some fundamental aspects of the economics of knowledge generation and distribution.

The overlap between codification and cosmopolitanisation consists in the fact that, from the perspective of the local level, cosmopolitan knowledge "has more formalized and abstract features compared to the local practices from which it emerged and to which it might apply (e.g. law-like statements, handbook data, theories-in-use, also rules of the thumb and standardized metrologies and charts)." (Rip, 1997: 16). At the same time, codification is not limited to the cosmopolitan level since it also occurs in local practices. Recipes, rules-of-thumb, instructions, blueprints, etc. are examples of such codified local knowledge. The key transition in cosmopolitanisation is from local to translocal, and the transition from informal/tacit to codified is secondary. Codification can be perceived as a "technical device" (see section 2.2.1) which enables the production of translocal knowledge.

Codification involves model building, language creation, and message writing (Cowan and Foray, 1997). Codified knowledge is knowledge which is recorded in a "codebook".[22] Codified knowledge potentially has characteristics of a collective good, but is it clear that decoding skills are required to use it. I.e. actors have to be capable of handling the model and understand the language in which messages are written. Codification does not necessarily result in a translocal knowledge reservoir. For individual actors, codification of knowledge may serve two objectives. On the one hand, it can be used "to share knowledge collectively and to transfer it at minimal cost among the members of a network. On the other hand, it can also be used to maintain this knowledge in the private domain if the code cannot be understood by others." (Cowan and Foray, 1997:

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[22] "Knowledge that is recorded in some codebook serves inter alia as a storage depository, as reference point, and possibly as an authority. But information written in a code can only perform those functions when people are able to interpret the code; and, in the case of the latter two functions, to give it more or less mutually consistent interpretations. (...) This means that what is codified for one person or group may be tacit for another, and an utterly impenetrable mystery for a third. Thus context — temporal, spatial, cultural and social- — becomes an important consideration in any discussion of codified knowledge (Cowan *et al.*, 2000).

598).[23] In practice, codification often serves both the objectives: "sharing the knowledge among a certain group (of firms, of scientists) and keeping (intentionally or unintentionally) other agents out of the club. However, the existence of high fixed costs to produce a specific language (in order to protect the codified knowledge) would discourage any kind of strategy of private codification and would increase the incentive to make the code public or semi-public. Thus, because of the high costs involved, codification tends to be achieved in collective action. An example of a large actor which took up codification is Shell, which became interested in codification of parts of its chemical plants to reduce its dependency upon contractors who used idiosyncratic codes. Interestingly, it cooperated with other (large) firms in the process industry to create translocal descriptions.[24]

Codification has clear (potential) benefits for actors. Codification makes knowledge easier to trade and transfer, and it allows for knowledge to be used as a signal of the desirability of entering into other forms of commercial relationships such as joint ventures, consultant relationships, or strategic technology development partnerships. Codification tends to reduce the (marginal) costs of technology transfer, and it allows actors to acquire knowledge more easily (once they have learnt to decode). Thus, a more efficient cognitive division of labour becomes possible in a situation where actors share the underlying code. Finally, codification may speed-up knowledge creation processes. To sum up, codification makes it easier and less costly to transfer, verify, acquire, store, reproduce and recombine knowledge (Cohendet and Steinmueller, 2000). The presence of (potential) benefits, however, is insufficient to generate collective action to achieve such benefits and thus cannot suffice as an explanation of why codification occurs (Olson, 1965). Moreover, there are also costs which might offset benefits. Encoding knowledge may be a costly process, particularly when the knowledge is deeply contextually embedded in experience and related understanding. Decoding knowledge in contexts other than those originally anticipated may also be costly — because translocality remains a precarious achievement and is not guaranteed by codification. In addition, codification increases knowledge's availability for "capture" by rivals. By codifying knowledge, companies may more easily lose control of proprietary knowledge. Internally, there are also problems associated with inducing individuals to share their expertise with others (Cohendet and Steinmueller, 2000).

A further complication is that costs and benefits are dynamic. In fluid situations, when the "knowledge environment" is unstable, the costs are rela-

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[23] Cowan and Foray (1997: 598) add: "It other words, a code can serve the objective of the marketing department of a company which wants its advertising message to be read and understood by everyone; but it can also serve the objective of the alchemist of the Middle Ages who has written a book of 'secrets' — a way of allowing himself (or perhaps a select few) and no one else to his past discoveries."

[24] Shell cooperated with other companies in SPI-NL "Samenwerkingsverband Process Industrie-Nederland". (For further details see website of SPI-Nl at www.uspi.nl).

tively high while the benefits are relatively low (Cowan *et al.*, 2000). Conversely, in stable (specific) situations, the costs are relatively low while the benefits are relatively high. The costs in fluid situations are higher because there are no accepted or authoritative models and languages. The construction of such models and languages is likely to be a costly endeavour. Once models and languages have been created, and the knowledge environment has stabilised, only variable costs remain. The benefits of codification in fluid contexts are lower because languages and models will contain ambiguity, and might exist in multiple forms. Stability is created through elimination of the multiple forms, and further elucidation of the models. Thus, codification itself is part of the dynamic in which situations are stabilised. A large share of the costs of codification must be born when the situation is still fluid, and when benefits are not (yet) clear: "the instability implies that codified knowledge might be difficult to use, due to the ambiguity of the language, and might have only a small number of users, due again, to the fact that there are multiple interpretations, and presumably, the potential audience will be divided among the interpretations." (Cowan *et al.*, 2000). In economic terms, there is an "inter-generational externality" problem, which means that the ones who have to invest, are not necessarily the same who can (later) reap the benefits. The conclusion is that a simple cost-benefit explanation will be insufficient to understand codification. The creation of a codified knowledge reservoir is a matter of technological and institutional evolution which involves changes in incentive structures, and in costs and benefits. There are path-dependencies and thresholds.

Cowan *et al.* (2000) argue that once situations have stabilised, codification is likely to occur and be sustained in situations where there are many costs to be reduced and/or many benefits to be gained. A typology can be made of stable situations in which it would be very costly and inefficient to keep knowledge tacit, or, in other words, where codification strategies are likely to be productive, and thus will be sustained once they occur (Cowan *et al.*, 2000). The first type of situation involves multi-actor and multi-location systems with substantial requirements for cooperation and knowledge exchange. A second type of situation involves systems which rely heavily on re-combination and re-use of knowledge, and which take advantage of the cumulativeness of existing knowledge (rather than on independent innovation). Codification would also be productive in situations characterised by systems that require recourse to detailed memory. A fourth type of situation involves systems which need particular kinds of description of what (and how) the agents do, either to meet quality standards constraints, to patent innovations, or to enter into contractual relations with a partner. Also included are systems in which effects of information asymmetry (between trading partners) cannot be mitigated with the traditional mechanisms of legal warranty, insurance, reputation and testing. The fifth typical situation is characterised by systems which information (and communication) technologies are intensively used.

For an understanding of cosmopolitanisation processes, these insights in the complexities of codification are relevant. Clearly, costs and (potential) benefits are an important issue. But it is also clear that the height of the costs is part of the dynamics — as cosmopolitanisation proceeds, costs will decrease and benefits will increase. There will be path-dependencies and thresholds. Costs and benefits alone will not be sufficient to understand cosmopolitanisation. (As Callon (1998) argued, rational-actor models only work in stable situations). In addition to costs, uncertainty reduction is important. In fluid situations, actors might value cosmopolitanisation for its contribution to reduction of uncertainty and disorder. What is less visible in codification literature is the role of intermediary actors in the production of codified, translocal knowledge. Their role can be important since they enable collective action and/or can take first steps in circulation and aggregation. Once stabilisation occurs, cosmopolitanisation is likely to be sustained in situations where translocality of knowledge is particularly beneficial.

Part of the affordance structure, therefore, should be the dynamic structure of costs and benefits in the situation. The structure of cost and benefits can only work as explanation in articulated situations where actors know their preferences, and steering actors know how to set and introduce incentives — which is rarely the case in practice. In fluid situations, actors might want to reduce (strategic) uncertainties by interacting and coordinating, and these interactions have effects on further (socio-cognitive) activities.[25] Once the situation stabilises (for whatever reason) the structure of costs and benefits can be used to understand why cosmopolitanisation processes will be sustained. The five types of situations identified by Cowan *et al.* (2000) offer clues for affordance structure in stable situations. It has to be taken into account that cost and benefit structure are likely to take on a different complexion for different actors.[26] As I argue in section 1.2.1, affordance structures are relational: they afford differently for different actors. It depends on the specific situation individual actors find themselves in (e.g. in terms of market segment or reputational capital achieved already) and on the structure of the community (e.g. whether or not there is a dominant leading actor). Actor constellations are not homogeneous and not static. Intermediary actors are a special type of actor for whom the affordance structure might be higher than for other actors. The presence and emergence of intermediary actor, therefore, needs more attention than it receives in codifica-

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[25] DeBresson and Amesse (1991) have the empirical observation that in periods of great uncertainty there are more intensive network activities. They argue that innovation networks occur when there are technological and market uncertainties; when technology has a system dimension — which calls for inter-organisational coordination; and when there is a "positive-sum" game. Added advantages of innovation networks include the possibilities for know-how exchange and mutual R&D evaluations, a more extended set of experiences to learn from, a broader scope of applications and experiments, reduction of sunk investments and irreversible technical commitments, reduction of opportunistic behaviour, and stimulation of shared language, shared expectations, trust, and possibilities to solve standardisation problems (DeBresson and Amesse, 1991).

[26] Discussions with Arie Rip.

tion literature. Outcomes of earlier socio-cognitive activities should also be included, since these can shape further cosmopolitanisation processes.

Cosmopolitanisation involves the production of a collective knowledge reservoir, i.e. knowledge which is shared. Economists have studied the issue of knowledge sharing and "openness" because it is "vital for the efficient use of costly research resources in creating reliable knowledge." (Foray, 1997: 66).[27] Although the epistemic aspect of translocality tends to be neglected in economic approaches, there are interesting insights about under which circumstances actors can be expected to share knowledge with rivals. For economists, knowledge sharing is intriguing, because market forces tend to undermine openness.[28] At the same time, knowledge sharing and conventions of openness do occur.[29] Some "shared history" is important for knowledge openness to emerge (Foray, 1997). Once openness is created through collective action (with its inherent difficulties), consolidation of the convention is based on adequate institutional settings and on the collective perception of the mutual benefits associated with knowledge openness. The path-dependent nature of the institutional system might result in the persistence of the convention of openness (Foray, 2002).

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[27] Foray (1997: 66) argues that "[o]pen access that distributes knowledge widely and rapidly facilitates independent replication of findings; promotes swift generalization of results; avoids excessive duplication of research; increases the probability of creating useful new products, processes, and ideas arising from novel and unanticipated combinations because new knowledge is available to many researchers; thus raises the social value of knowledge by lowering the chance that it will reside with persons and groups who lack the resources and abilities to exploit it."

[28] "There is (…) a persistent, market-driven pressure toward reducing openness in the knowledge system by altering the norms, incentive mechanisms, and property right systems in a direction that will encourage non-cooperative modes of pursuing and transmitting scientific and technological knowledge." (Foray, 1997: 74). Benefits of knowledge sharing on the level of individual actors include the reduction of uncertainties, risks, complexities, and cost.

[29] In a historical overview, Foray (1997) sketches how the convention of openness evolved since the Middle Ages, when craftsmen tried to keep their knowledge secret in order to maintain the monopoly of guilds. In the Renaissance, Foray argues, it was realised that secrecy and access restriction had resulted in the stagnation of knowledge rather than the protection of valuable secrets. In an attempt to profit from the cumulative nature of knowledge, intellectual property rights were given to those who disclosed their knowledge. A patent not only is a device to prevent free use of new ideas and methods, but also a means of disclosure of codified knowledge. "Although the patent only reveals the codified information needed to make use of a novelty, it provides an invaluable indication of the potential success or 'practicability' of a given line of research. It gives information on the 'state of the art', and thus allows rivals to allocate their research resources more efficiently (…)" (71). During the Scientific Revolution "open science" emerged, in which scientists were persuaded to disclose findings, through a "reputational reward and resource allocation system based on validated claims to priority in discovery or invention." During the nineteenth century an institutionalised process of "collective invention" emerged in some technological domains. In the twentieth century, the Japanese have created openness characterised by an absence of any legislation relating to trade secrets and a patent regime characterised by low cost of filing, priority given to the first to file, and freedom given to applicants to make changes to a proposed patent. In informal networks and consortia there may also be local conventions of knoweldge openness. Von Hippel (1987) has demonstrated that secret sharing and informal know-how trading does occur in engineering communities.

Although the emergence of openness is difficult to explain, several types of situations in which actors share their knowledge with others can be identified (Foray, 2002). First, knowledge sharing occurs in cases where actors are member of a community (and want to remain so) and value reputational rewards. In technological domains, professional engineers are known to value reputation within their professional societies. Thus, it is important understand how communities emerge and why actors want to be (and remain) a member.[30] The establishment of societies and associations, therefore, is likely to be an important aspect of cosmopolitanisation. Second, sharing of knowledge occurs in cases where "informal trading networks" emerge in which engineers trade proprietary know-how, based on reciprocity obligations. Von Hippel (1987) has studied this type of situations. In his study, he focussed on situations in which firms considered a significant portion of their know-how proprietary and protected it as a trade secret. When required know-how was not available in-house, engineers either could develop it themselves, or they could learn from other specialists working for rivalling firms. The latter strategy tends to be much less expensive. Von Hippel found that such professional colleagues were indeed willing to reveal their proprietary know-how to employees of rival firms.[31] The presence of informal trading networks between engineers having common professional interests, played a crucial role in the know-how trading practices. Such networks are not self-evident.

> "Network formation begins when, at conferences and elsewhere, an engineer makes private judgements as to the areas of expertise and abilities of those he meets, and builds his personal informal list of possibly useful expert contacts. Later, when "Engineer A" encounters a product or process development problem he finds difficult, he activates his network by calling Engineer B, an appropriately knowledgeable contact who works for a directly competing (or non-competing) firm, for advice. B makes a judgment as to the competitive value of the information A is requesting. If it seems to him vital to his own firm's competitive position, he will not provide it. However, if it seems useful but not crucial — and if A seems to be a potentially useful and appropriately knowledgeable expert who may be of future value to B — B will answer his request as well as he can and/or refer him to other experts of his acquaintance. B may go to considerable lengths to help A: He may, for example, run a special simulation for him on his firm's computer system. At the same time, A realizes that in asking for and accepting the help, he is incurring an obligation to provide similar help to B — or to another referred by B — at some future date. No explicit accounting of favors given and received is kept in instances studied to date,

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[30] Discussions with Arie Rip.

[31] The fact that knowledge can be traded, implies that some aggregation work must have occurred, otherwise it would be difficult to transfer knowledge to a different context, and that the application contexts of the trading partners have a relatively high degree of similarity.

> but the obligation to return a favor seems strongly felt by recipients — "... a gift always looks for recompense" (Von Hippel, 1987).[32]

An addition to Von Hippel's argument can be made. Informal contacts between engineers not only involve interactions motivated by problem solving. There is also the aspect of "intelligence" — gathering information on what other are doing or a planning to do. For example, in the electronics industry it is not uncommon that engineers of rivalling companies exchange information on their research and plans for research.

> "When the CEOs of General Electric and Philips Company met to negotiate markets, their patent battles and other issues in the 1930s in one or the other's headquarters, they always had engineers with them who would go and visit the laboratories and workshops of the other party. The engineers would not see everything, but would be able to get a grasp of what was going on, and establish contacts with their counterparts for later use. Such double interactions continue today, and are based also on shared professional backgrounds of the engineers." (Rip, 1997: 6).

The creation and maintenance of informal networks requires efforts and costs. Engineers have to visit conferences, go to professional meetings, or participate in committees of professional societies or standardisation organisations to create and maintain their networks (Rip, 1997). In other words, this second type of situation overlaps with the first type where membership enables sharing. Informal knowledge trading implies some (initial) cosmopolitanisation — some translocality must have been achieved, otherwise knowledge would be very difficult to apply by the recipient — , and once it occurs, it contributes to further cosmopolitanisation.

A third type of situation in which sharing of knowledge occurs exists when actors can achieve a strategic advantage by disclosing knowledge to others. This is the case when incumbents decide to pool their intellectual property rights in an attempt to raise entry barriers. Actors can also reveal knowledge hoping that others will adopt it and thus set an industry standard. (Cf. participating on the cosmopolitan level to influence outcomes). Actors are also known to reveal technological knowledge to suppliers (or even rivals) to induce manufacturer improvements.

The emergence of these typical situations (i.e. emergence of communities, reciprocal networks, strategic advantages to disclose) provides clues for identification of situations in which cosmopolitanisation processes are likely to be sustained. What is clear is that cosmopolitanisation might start out as a cumulation of unintended (and some intended) effects (cf. structuration theory), and that an affordance structure emerges "behind the backs" of the actors. Actors draw on the affordance structure, are constrained by it, and might become in-

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[32] Von Hippel (1987) adds that "[t]he essential difference between know-how trading and collective invention is that know-how trading involves an exchange of valuable information between traders which is at the same time kept secret from non-traders. In contrast, collective invention requires that all competitors and potential competitors be given free access to proprietary know-how."

creasingly reflexive about it. As the situation stabilises, the structure of costs and benefits may become recognised parts of the affordance structure. The conceptual problem how affordances have effects on action and how the actions and interactions add up to new situations (even changes in affordances), is not solved. But it is possible to make progress by inquiring into plausible links between types of affordances and patterns in, and extent of, cosmopolitanisation.

2.3.3 Affordance structure for cosmopolitanisation

The aim of this section is to identify plausible links between affordances and patterns in, and extent of, cosmopolitanisation. As discussed in section 1.2.1, there are different affordances, which may be interrelated or compounded. I also noted that affordances are relational: they are different for different actors. Affordances are not static, but part of ongoing structuration processes. The relevance of affordances might shift as the situation stabilises.

I propose three (interrelated) types of affordances: technology, actor constellation, and historically evolved infrastructures and rules/cultural repertoires at the level of the socio-technical landscape (which include outcomes of earlier cosmopolitanisation processes). With regard to technological affordances I will take the technological hierarchy as a basis, because technologies at different levels of the technological hierarchy (i.e. materials/components, devices, artefacts and systems) are likely to work out differently, for example in terms of division of labour they enable and require, in terms of standardisation (as of materials, components and devices), in terms of interests in continued delivery of materials and components to customers, and in terms of sociopolitical interference.

I take the actor constellation as a second constituent part of the affordance structure, because theories on collective good production have argued convincingly that different constellations offer ("suggest") different opportunities and constraints for collective action. Obviously, the actor constellation is not pregiven, but evolves as cosmopolitanisation unfolds. Nevertheless, there are underlying patterns (Pavitt, 1984; Van de Poel, 1998).

Outcomes of earlier cosmopolitanisation processes (infrastructure, repertoires, institutionalised intermediaries) are a third part of the affordance structure. These affordances are on the level of the landscape and my appear as given background for actors at a certain time. For example, the extent of professionalisation in a given domain at a given time is likely to affect cosmopolitanisation of new technologies in such domains.

The affordances are not independent. They are likely to co-evolve. For instance, it is a received insight that technology and industry structure are not independent. Large technical systems are produced in different industry structures than materials. That I nevertheless make an analytical distinction is because I want to highlight that technological aspects and actor constellations create their own specific affordances.

Technological affordances

Different levels in the technological hierarchy (materials/components, devices, artefacts or systems) create different affordance structures for the production of translocal knowledge. So what does it mean to create a configuration that works at on or another level in the hierarchy? At the lowest level, it means combining different (raw) materials into a new compound or composite material or component. Since the inner workings of the configuration are largely invisible to the human eye (and involve complex processes on a molecular level), it is often poorly understood how the performance can be related to its constituent materials, the processing steps and contextual variables.[33] The inner workings of paints, for instance, remained enigmatic for a long time, and to some extent still are. (Another way of saying this is that is will be difficult for practitioners to specify interoperability requirements for raw materials). Practitioners tend to rely strongly on accumulated empirical knowledge to achieve a uniform performance across time and space. When qualities of raw materials vary and/or when circumstances and conditions change, it will be difficult to achieve the same performance.[34] Repeatability of a performance is partly determined by the quality of the raw materials. It makes a difference whether the qualities of raw materials are standardised or not. The availability of commodified raw materials makes formulation processes less unpredictable. Also precise equipment and instrumentation contributes to this. The enigmatic nature of materials also results in the fact that they are difficult to reconstruct (or reverse engineer) by other actors — although analysing techniques have greatly improved over the years. Knowledge on materials, therefore, can be kept secret: the knowledge embodied in materials is difficult to reconstruct. Even though materials will circulate, knowledge may remain local. Even if practitioners were willing to share knowledge, this might be difficult. Knowledge transfer will require that contexts will be made similar.

For artefacts, creating a configuration that works means to assemble components which are designed to interoperate as a working whole. The specification of interoperability requirements is important, especially if components are made by another party. Precision equipment is likely to be required if tolerances are small. Whereas the alignments between the constituent parts in a material or a component are difficult to reconstruct once the material or component has been made, the alignments between, and interoperation of, the constituent parts in an artefact are more visible to the trained human eye. If practitioners get their hands on an artefact made by others, they usually can reconstruct how the performance is achieved — although actual imitation might still be difficult since the knowledge embodied in the constituent materials and components might not be easy to reconstruct, and/or because specialised production technology

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[33] On the role of visual thinking and understanding see Ferguson (1994).

[34] In the (mass) production of beer, for instance, it is a major challenge for brewers to achieve the same quality with varying qualities of natural ingredients.

might be required. In general, knowledge embodied in artefacts can be reconstructed elsewhere with more ease than knowledge embodied in materials or components. This also implies that devices can more easily be compared than materials, and this allows for re-combination of knowledge into a more effective and robust form.

In case of systems, creating a configuration that works means to couple subsystems which are designed to interoperate into a working whole. The configuration is complex and heterogeneous, and achieving a performance requires planning and coordination of multiple actors.[35] Technological knowledge is more heterogeneous than on lower levels. Trial and error tends to be a costly or risky strategy in making a configuration that works. With artefacts it might be relatively easy to experiment with different configurations, for instance in successive series. For systems with a relatively long life-span this can only be done in small-scale trials — which might be difficult to scale up. On the level of systems, complex technologies tend to be produced in (multidisciplinary) projects, and

> "[t]he larger the project and the more systemic and complex the product, the more important tacit knowledge is likely to be in [complex products and systems] CoPS project design and execution. In some cases (e.g. passenger airports), overall concept knowledge may reside in a small number of well-known individuals worldwide. In other cases, there may only be a handful of engineering teams capable of designing and building new versions of complex products (e.g. in flight simulation). Because of the inability to experiment and because of feedback loops from later to earlier stages, step-by-step continuous learning during CoPS projects is likely to be central to their design, production and installation." (Hobday, 1998)

Thus, it tends to be difficult to learn from one project to another, let alone to share this knowledge with other actors (Davies and Brady, 2000).

Once achieved, systems are more inert than lower-level technologies. Making changes in one constituent part of the configuration usually requires that other elements have to change as well, and this tends to be a costly affair, since the subsystems have to be redesigned as well. This puts a premium on reduction of complexities and uncertainties beforehand. Hobday (1998) has highlighted distinctive features of the creation and development of high cost, complex products and systems (CoPS). The dynamics of innovation and knowledge production in CoPS are likely to differ from the dynamics in case of materials and (non-complex) artefacts because CoPS are "highly customised, engineering-

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[35] "The more complex a product, the greater the number of subsystems, interfaces, dimensions of merit and linking requirements. The more complex and/or open the product, the greater the technical uncertainty and the greater the intrusion of organizational dynamics in technological evolution." (…) "Complex systems, whether for firefighting, transportation, communication, or transmission, require consensus by multiple actors so that technological subsystems are compatible. The more complex the technology, the more important linking technologies become. For complex technical systems, sociopolitical and interorganizational processes emerge to shape technical progress." (Tushman and Rosenkopf, 1992).

intensive goods which often require several producers to work together simultaneously" (Hobday, 1998).[36] In other words, the heterogeneity of knowledge producers is larger: complementary producers, users, suppliers, regulators and professional bodies may all be involved in knowledge production. System designs and methods of production and implementation tend to be negotiated ex-ante. It is clear that the actor constellation (see next subsection) will be different in higher levels, also because markets are often bureaucratically administered and contestability is low in contrast to commodity goods which are characterised by arms-length market transactions (Hobday, 1998).

Depending on the level of the hierarchy, four general technological aspects work out differently. The higher in the technological hierarchy, the more *complex* the configuration, in terms of number of elements and (socio-)technical alignments. The level of complexity shapes the conditions for knowledge production. The more complex the configuration, the more substantial the requirements for coordination and exchange between multiple parties and locations. Whereas the production of simple configuration can remain a single-actor affair, the production of complex configurations tends to be a multi-actor and multi-location affair. In other words, there are interdependent knowledge producers. In case of large complex systems, a hierarchical cognitive division of labour might evolve with system architects in a central position. This creates an affordance to produce knowledge which is not tied to one location, but can be shared with others in other locations. But it is a translocality which is optimised for the particular system configuration. This means that complexity does not create an immediate affordance for the production of translocal knowledge about a class of configurations. However, the need to reduce complexity and increase manageability might create such an affordance. The emergence of systems engineering after the Second World War, provides an engineering repertoire for actors involved in large complex systems to create translocal knowledge.

For technologies on lower levels which are part of complex systems on higher levels, the complexity affordance might be carried over. That is, requirements with regard to interoperability, reliability, uniformity, etc. from the system level create an affordance for the production of translocal knowledge on

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[36] In dominant design literature — which neglects the issue of translocality — it is argued that in the case of nonassembled or simple assembled products, a dominant design can be established by superiority on easily measured "dimensions of merit". The producer is relatively independent from other (complementary) producers and the influence of sociopolitical dynamics on the process is minimal (Tushman and Rosenkopf, 1992). The more complex a technology is, the less univocal and evident the dimensions of merit are. The establishment of a dominant design for complex technologies will be determined by a broader and more heterogeneous range of interdependent actors. In other words, there is no simple market selection. Especially in the case of systemic technologies, where multiple, interdependent components are linked via interfaces, technological developments will be shaped by sociopolitical processes. The locus of innovation will be moved beyond the firm to the community level (Rosenkopf and Tushman, 1998).

lower levels in the technological hierarchy. In general, the way technologies are embedded in higher level configurations shapes the affordance structure. (There are overlaps with the actor constellation affordance, in particular with regard to the type of customer). For the highest level, such an affordance obviously does not exist, although a requirement to interconnect systems into one overall "system of systems" might create a similar affordance to produce knowledge which transcends particular system configurations.

The second affordance is shaped by the fact that different technologies work out differently in terms of opportunities for standardisation and interests in continued production. Materials, components, and artefacts tend to be produced in factories from which they are sent-out to customers.[37] In lower levels of the technical hierarchy, the production of configurations is likely to be a repeated affair, e.g. products which are made in successive series. Systems, on the other hand, are not made in large series, and are often configured on location. This creates different affordance structures for manufacturers as knowledge producers. In situations where configurations can be sent out to many locations, strategies aimed at standardisation, quality improvement and (continued) learning from experiences are more likely to be productive than in situation where a configuration is made for one specific application. In case of complex, systemic technologies, where such affordances for manufacturers as knowledge producers tend to be relatively weak, there might be affordances for intermediary actors to act as consultant for producers.

This affordance is related to the degree of mobility of the technological configuration. Mobility is not just a matter of product size, weight, (transportation) cost, markets, etc., but it also involves a cognitive aspect: producers have to (learn to) anticipate on a variety of application conditions, which calls for the production of knowledge about how to make configurations which can perform in a wide range of contexts. In other words, mobility presupposes decontextualisation. Depending on the uniformity and predictability of the application context, this works out differently. Aspects like size, weight, cost, and markets determine the potential for standardisation and continued production, but whether this potential can be made manifest depends on cognitive work, i.e. aggregation of experiences, test results, and experimental findings and the development of a technical model. In general, the mobility affordance will be higher in the lower levels of the technical hierarchy — although this might work out differently for intermediary actors like consulting engineers (once they are present).

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[37] Note that this is historically contingent. Over the centuries, many craft technologies (which have close ties to contexts of use) were industrialised. Factories were established in which products were mass-produced.

A third technological aspect which shapes the affordance structure is the level of uncertainty and risk in terms of costs and safety. A high level of uncertainty and risk creates an affordance to reduce uncertainties and risks beforehand. Such reductions might be achieved by creating robust and translocal knowledge (e.g. a technical model which allows for predictions or calculations of the performance). Risks play a different role on the levels of materials, devices, artefacts and systems. In general, systems tend to be more risky than materials and artefacts. Failures of systems can be very costly and consequential. Whereas failure of materials and artefacts (which are not incorporated in a system) might provide a valuable lesson (cf. trial-and-error), the value of such a lesson for systems might not weigh up against the costs of failure.[38] The failure of air traffic control systems, for instance, might result in the collision of aircraft. McGee (1999) has argued that such cost considerations played an important role in the emergence of an architectural design approach in shipbuilding (especially in case of warships). Learning by doing and trying was considered too risky, and was replaced by efforts to model and calculate the performance of ships beforehand. This contributed to the achievement of translocality.[39] In general, there will be a trade-off between calculated security and testing. Once technical models have been developed (which requires efforts and costs) calculations are cheaper than real tests, while they do not give the (quasi-)assurance of testing.

A fourth technological affordance lies in the technological hierarchy itself. Since systems consist of materials, components, devices and artefacts (grouped in subsystems), systems provide an application context for materials, components and devices. Technologies at a higher level in the hierarchy create affordance structures for technologies at lower levels in the hierarchy. To understand this affordance better, it is helpful to use Mumford's (1967) notion of megamachines which refers to the disciplining effects of sociotechnical systems on its constituent components.[40] The megamachine is an organisation in which materials, components, devices and humans with their skills and tools are coupled into one working whole. It involves a high degree of specialisation and

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[38] It might be added that trial-and-error learning has its limitations. "Learning through trial and error (…) has its risks (when the trials are dangerous) and are epistemologically limited because they follow a particular learning trajectory." (Rip, 2002a: 111).

[39] In shipbuilding classification societies have come to play an important role in reducing risks beforehand. The basic task of classification societies was to make classifications of ships in order to inform underwriters on the risks involved. Their classification rules became guidelines for shipbuilders. The classification rules were based upon accumulated information and experience concerning the service performance of ship's designs. Eventually, classification societies became actively involved in technological knowledge production themselves, as they began to operate as engineering consultants for the industry (Andersen and Collett, 1989).

[40] Mumford's (1967: 188-211) notion of megamachines is discussed in Achterhuis (1992: 243-4). Achterhuis links the megamachine to Latour's (1987) actor-networks.

division of labour. Interoperability is of key importance, and is achieved by circulation of knowledge. Thus, the functioning of a megamachine implies that knowledge is mobilised and has achieved a degree of translocality. On the level of the overall system, system architects must create an overview in order to be able to align all the elements into one working whole. In Ancient times, the building of pyramids, for instance, involved a large bureaucratic organisation, with relied on circulation of messages and knowledge, and elaborate bookkeeping. In megamachines, the production of knowledge on configurations in the lower parts of the technological hierarchy is structured by demands and requirements from the higher level.

These affordances occur together, and are interrelated, or at least become interrelated. But they do point to aspects that can be checked for separately — as I will do in the case studies in chapters 4–7.

Actor-constellation affordances

Different actor constellations will create different affordance structures for the production of translocal knowledge. A general insight of the theory of collective goods was that the size and heterogeneity of the actor constellation will influence the possibility of collective action. The larger the constellation, the more difficult collective action will be. The presence of dominant actors will make the production of collective goods less difficult. What is also clear from previous discussions on collective action is that it might be a phased process: actors might first try to create a collective actor (e.g. an association) which then further enables collective action. Weyer *et al.* (1997) and others demonstrated that actor constellations which carry technological developments evolve and change. Garud (1994) argued that levels of competition shift when fluid situations become specific. Collaboration between rivals increases in stabilised situations. Thus, the dynamics of actor constellations has to be taken into account.

A first question is: which actors should be taken into account? Producers of products and services are important producers of technological knowledge. But the range of technological knowledge producers is (or may become) larger and more heterogeneous (which is a difference with scientific knowledge production). In literature on national innovation systems (see section 2.2.2) and sectoral innovation systems a whole range of (potential) knowledge producers is identified, including various intermediary actors (Edquist, 1997; Malerba, 2002).[41] My focus is not so much on innovations, but on the production of translocal knowledge as a collective good. A way to conceptualise how actor constellations create affordances for cosmopolitanisation, and to specify which

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[41] Malerba (2002: 247) defines a sectoral system of innovation and production as "a set of products and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products. A sectoral systems has a specific knowledge base, technologies, inputs and demand." There is a heterogeneous set of actors which "interact through processes of communication, exchange, co-operation, competition and command, and these interactions are shaped by institutions. A sectoral system undergoes change and transformation through the co-evolution of its various elements." (247).

actors are relevant, is to ask when, and for whom, cosmopolitan knowledge is functional and useful. For instance, suppliers might fulfil their roles better if knowledge is cosmopolitan. Customers might be more easily convinced of the reliability of a technology. For intermediary actors like engineering firms, translocal knowledge might also offer advantages. The usefulness or beneficialness of translocal knowledge for different categories of actors does not imply that actors will work towards it. There may be thresholds to overcome or constraints like cost and appropriability.

Based on insights from collective good theory, the presence of dominant actors is likely to be an important element in the actor-based affordance structure. Ceteris paribus, the presence of dominant actors, with an interest in translocal knowledge, will create affordances. Several actors might be dominant, and dominance can occur in 'horizontal' interdependencies between rivals and in 'vertical' interdependencies between suppliers, manufacturers, and customers. During 'industry life cycles' dominant manufacturers might emerge (e.g. a monopoly or oligopoly) which creates an affordance for the production of collective goods. Such producers can take the initiative to produce translocal knowledge.

Within the value chain, there can be different patterns of interdependence. Van de Poel (1998) elaborated Pavitt's (1984) typology of innovation in sectors and identified four innovation patterns. These patterns reflect different interdependencies and role-relations between suppliers, producers, and customers. The four innovation patterns differ with regard to the main locus of innovative activity, and the ways in which innovations will start. These patterns are sedimented outcomes of earlier interaction patterns and divisions of labour in technological domains.

Within an actor constellation, dominance of customers creates affordance. In "user-driven innovation patterns" (Van de Poel, 1998), there are performance-sensitive customers which can be demanding in terms of assurance of reliability and safety, and thus create an affordance for the production of reliable and robust knowledge.[42] On behalf of customers, third parties like insurance companies might come to play a similar demanding role. For instance, in ship building, classification societies have come to play an important role in the production of translocal knowledge (Anderson and Collett, 1998). Demanding customers can reveal knowledge to their suppliers (and even rivals) to induce manufacturing improvements, thus contributing to a collective knowledge reservoir (Foray 2002). In the user-driven innovation patterns, professional cus-

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[42] Cf. Cowan *et al.*'s (2000) typology of situations (with stable knowledge environments) where codification strategies are likely to be productive: the fourth type of situation involves systems which need particular kinds of description of how the agents achieve a performance (either to meet quality standards, to patent innovations, or to enter into contractual relations with a partner), and systems in which effects of information asymmetry (between trading partners) cannot be mitigated with the traditional mechanisms of legal warranty, insurance, reputation and testing.

tomers are a main locus of technological activities, and innovations will usually start with new functional requirements. Such a pattern is likely to involve a division of labour in which "specialised suppliers" supply to (and cooperate with) professional users (Van de Poel, 1998). This pattern creates an affordance for suppliers and customers to cooperate. Knowledge production is shaped to a large extent by the demands of the professional customer. The specialised nature of suppliers creates an affordance to aggregate knowledge, especially if they are active for a range of customers. Their knowledge base is important for their competitive advantages and they will try to exploit it, and they will be induced to participate on a cosmopolitan level, once it emerges, in order to create visibility, reputation, and to stay informed of the state-of-the-art.

Governments, in their role as client, can also be dominant and demanding, e.g. in a "mission-oriented innovation pattern" (Van de Poel, 1998). In mission-oriented innovation patterns there is a division of labour between "common good providers" and "mission actors" (the government as client). Mission actors have a central position and are in a position to influence technological developments. They can act as a "cosmopolitan tutors" to "localist procurers" (Disco, 1990). As knowledge producers, large customers are in a good position to compare and evaluate different solutions developed by different producers. The results of such evaluations can be fed back to the producers and contribute to the emergence of a shared knowledge reservoir. This pattern is likely to involve complex technological systems, e.g. infrastructural works. Thus, the affordance for collective action is likely to be reinforced on account of the complexity of the technology. Building up and exploiting a knowledge base is important for mission actors (to supervise contractors) as well as producers (to build a reputation and remain competitive). Thus, the presence of dominant and demanding mission actor creates an affordance.

Also, suppliers might be dominant, e.g. in a "supplier-dependent innovation pattern" (Van de Poel, 1998). In such patterns, suppliers are the main locus of technological activity and knowledge production, and innovations will usually start with new component parts. In these patterns, there tends to be a division of labour in which suppliers are science-based firms and customers are either supplier-dominated firms (which compete on nontechnical features) or scale-intensive firms (which rely on exploitation of economies of scale). This pattern creates affordances for suppliers to produce translocal knowledge (e.g. to be able to use scientific knowledge to produce new products) and for producers to create alignments with their suppliers. Suppliers are likely to be the main carriers of cosmopolitanisation once it occurs. They depend on their knowledge base and on access to scientific knowledge bases. The inducement to contribute to cosmopolitanisation will be to maintain their "science-based" characteristic, and thus, their role as supplier. However, knowledge production is likely to be on the level of components, rather than on the level of the overall configuration. Affordances on the level of the manufacturer tend to remain low.

Van de Poel (1998) identified a fourth, "R&D-dependent innovation pattern" in which large science-based firms play a prominent role. Innovations start with technological promises or presumptive anomalies bases on technological and scientific insights. For science-based firms their proprietary knowledge bases as well as their access to collective knowledge reservoirs are vitally important. The dynamic might be similar to that in scientific fields in which professionals compete not only for contracts, but also for credibility and reputation. This pattern affords for cosmopolitanisation.

When technologies have unintended and/or undesirable effects, regulatory or societal actors might become interested in how the performance of technologies is achieved. They might come to play a demanding role, as they restrict the options available for producers and induce the development of new solutions. They might also become knowledge producers themselves.

In sum, the emergence of dominant actors, especially when they are demanding, creates affordances for cosmopolitanisation. In addition, it should be emphasised that the actor constellation is a dynamic variable and it is interwoven with the process of cosmopolitanisation. The actor-constellation and cosmopolitanisation co-evolve, since cosmopolitanisation involves the emergence of a local-cosmopolitan division of labour. In particular the emergence of intermediary actors might create shifts in the actor-constellation affordance structure. For instance, when manufacturers succeed in creating an industry association, or when engineers succeed in establishing a professional society, the actor-constellation affordance increases. While collective actors might be established for other reasons than cosmopolitanisation, once they exist they can come to play a role in it. For example, industry associations might be established originally to protect collective commercial interests (e.g. vis-à-vis dominant customers), and evolve into a forum for pooling of experiences and deliberations on common technological problems and solutions. Through an industry association actors might be able to organise for collaborative (pre-competitive) research and the establishment of a collectively funded test station. In other words, they might provide an infrastructure for circulation and aggregation. The effectiveness of this mechanism depends on the ability of the collective organisation to make membership more or less mandatory so that free-riding will not occur. This is in line with Foray's (2002) argument that in situations where actors are member of a community (and want to remain so), actors are more likely to share knowledge, e.g. to gain reputational rewards in their community. The forums of collective actors might lead to the emergence and maintenance of "informal trading networks".

If actors do not succeed in creating a collective actor or otherwise do not engage in circulation and aggregation, this might create a space for intermediary actors to invest in production of translocal knowledge which they can sell to a variety of actors. Consulting engineering firms, for instance, might emerge and they are in an excellent position to aggregate knowledge. In addition, they have to advertise themselves by disclosing part of their knowledge. An absence of collective actors or infrastructure in general, might also call into action governmental intervention, whether or not as a result of lobbying. Such governmental intervention might result in the establishment of a sectoral research institute, which can come to play an important role in the production of translocal knowledge. After the First World War, for instance, the British Department of Scientific and Industrial Research encouraged "any group of firms associating for the purpose of sponsoring research into problems of common interest and undertaking to contribute to the cost." (Varcoe, 1974: 23). As a result several research associations were established in different industries.

What becomes clear in this discussion is that in addition to the general notion of affordances, there is a special and often important mechanism of thresholds to be overcome, after which a self-reinforcing dynamic starts. For instance, cosmopolitanisation might not take off until intermediary actors have emerged. Once there are actors at a cosmopolitan level, it becomes important for other actors to participate and contribute, and cosmopolitanisation might thus gain momentum. The emergence of intermediary actors and forums which might help to overcome thresholds to cosmopolitanisation is historically contingent. Nevertheless, there are general patterns, as discussed above, and secular changes which make cosmopolitanisation easier, and a recognised possibility.

Historical setting, including existing mosaics of regimes and infrastructures

Cosmopolitanisation never starts from scratch, and historically evolved divisions of labour and innovation patterns will affect how new cosmopolitanisation patterns take off and unfold. This constitutes a third kind of affordance, but of a historical rather than a systematic nature. An immediate implication is that, in order to understand cosmopolitanisation processes in a specific case, one should characterise the cosmopolitan elements which are present at the beginning, and trace what their influences are. Existing mosaics of regimes might offer point of departure for new cosmopolitanisation patterns, if only because existing knowledge reservoirs can be used and because actors anticipate that a new technological regime will also emerge in their sector and act accordingly. Existing intermediary actors might jump to the occasion and offer their services to an emergent sector. In fact, intermediary actors have professionalised and made intermediary action their business. This was clear in my earlier discussion in section 2.2.2, the "Knowledge Intensive Business Services" being one (recent) example.

In section 1.3, when discussing secular changes that affect cosmopolitanisation processes, I already suggested important affordances (without calling them so): the rise of professional engineering with its combination of acquiring status and extending and improving general engineering knowledge;[43] the estab-

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[43] An interesting example is offered by Marvin (1988). She describes how professional electrical engineers took control of new electric communication technologies in the late nineteenth century. While in the early stages of a new technology 'tinkerers' and others can be active, gradually professional engineers take over and appropriate the new technology. In the case of electrical communication a division of labour emerged between electrical engineers (with high status) and technicians (with low status). A continuation of this story is visible in how Fox and Guagnini (1992) characterise high-voltage alternating current, the cutting edge of electrical technology around 1900: "It was a world of large generators, long-distance transmission lines, electric traction, and the electrification of industry. In all of these areas, there were

lishment of research centres by governments, or stimulated by government measures; standardisation (in the broad sense); communication technologies and information and knowledge management.

In the twentieth century the involvement of professional engineers in new technologies has become a 'standard' part of cosmopolitanisation processes, from the very beginning, as in electronic engineering, or to improve existing approaches or develop an invention further. The local-cosmopolitan aspect is visible in a number of ways, including the contrast between, and secular change from a "shop" culture to a "school" culture. In a "shop" culture, local experience on the work floor is thought to be the key to better practice as well as for training. In a "school" culture, formal training is the key, often with an emphasis on general insights and methods, including mathematics.[44] Such teaching needs create an additional push towards cosmopolitanisation, but often at one remove from ongoing practices (Disco *et al.*, 1992). The cosmopolitan knowledge might be too abstract to be of much value on location.

During the twentieth century, the role of the nation state in science and technology increased. Besides overall science and technology policy and stimulation and infrastructural measures which have indirect effects on cosmopolitanisation at best, more concrete affordances come from the support of testing and standardisation, support for and sometimes involvement in, engineering and other technical education, and support for knowledge production in sectors. Such activities occurred also without special government support, for example by professional bodies and industrial trade associations (a regular feature of industrial life from the early twentieth century on). But government action was important to confer some authority (in standardisation) and to overcome thresholds to cosmopolitanisation by create spaces for circulation and aggregation, as in the sectoral research institutes which were established by governments in a number of countries, in particular after the First World War. This way to stimulate R&D collaboration became an important way to overcome thresholds especially for smaller firms. In some industries (especially the electrical and chemical industries), industrial research became an established feature already in the late nineteenth century, even if it took a few decades more before

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major new departures, but they were seldom ones that originated in the laboratory, at least in the laboratory as it is traditionally conceived. The laboratory that mattered for the pioneers of high-voltage A.C. before 1914 was the workshop or the site. Here, the activity was scientific to the extent that it involved experiment, theoretical insights, sophisticated mathematical techniques, and the systematic analysis of production methods. The workers in this "laboratory", however, were engineers rather than reconverted physicists. They constituted a very different breed who combined scientific competence with experimental interests focused firmly on the machines and installations themselves. They were the products of courses explicitly oriented to electrical technology, albeit to an electrical technology that demanded an increasingly refined grasp of physical theory." (139).

[44] See for the contrast as it was visible in nineteenth-century America, Calvert (1967). Studies by Lundgreen (1990) and Homburg (1993), focusing on German-language countries, have shown that the contrast is more complex and involves an Enlightenment component, and plays out differently in different areas of technology and engineering.

fully-fledged central R&D laboratories were established generally (Homburg and Rip, forthcoming 2003).

After the Second World War, during the post-war reconstruction, science and technology became more closely linked. Governments increasingly started to intervene in national (and sectoral) innovation systems with science and technology policies. The importance of (basic) industrial research became widely recognised. Established intermediary actors were looking for employ and tried to get involved in technological developments.

These secular developments added up, and created an impetus to cosmopolitanisation. As a consequence, actors became more reflexive about cosmopolitanisation processes, and started to anticipate on the emergence of collective knowledge reservoirs and technological regimes. This adds a socio-cognitive element to the anticipation on industry standards which has been studied extensively in the innovation and management literature (Tushman and Anderson, 1997).

What is clear from these observations is that the historical setting and the various dynamics of development imply affordances for cosmopolitanisation, but of varying and not always predictable kinds. As I noted before, in section 1.2.1, it is the whole array of affordances which shapes the space for cosmopolitanisation. This is particularly important to trace, and in historical detail, for the third kind of affordance constituted by existing cosmopolitan elements.

Chapter 3.
Research design

3.1 Introduction

In chapter 1 I introduced my research questions: how can exchange and sharing, the essential step towards the emergence of a technological regime occur, given the local origin of technological knowledge and the collective good characteristics of translocal knowledge? And when it occurs, can we understand why, and how it will be shaped? I introduced the concept of cosmopolitanisation to specify the socio-cognitive dynamics in which a two-level division of labour emerges with a local and a cosmopolitan level of epistemic activities, embedded in infrastructures and institutes. To understand cosmopolitanisation, I proposed an affordance-based explanation. I argued in chapter 2 that technology, actor-constellation, and historically evolved infrastructures are key elements of an affordance structure for cosmopolitanisation.

The conceptualisation of cosmopolitanisation and the affordance structure was based on theoretical insights, plausibility argumentation and empirical illustrations. To improve the robustness of my conceptualisation, the elements of the affordance structure cannot be tested as separate hypotheses since they are not independent. But the conceptualisation can be explored with the help of case studies, which are used as arenas for a 'trial of strength' of the conceptualisation. Will my specification of cosmopolitanisation and its affordance structure hold out, or are adaptations necessary to increase its robustness?

To address the research questions, and to assess the strength of my conceptualisation, I use a case study approach, because in this way the dynamics in ongoing processes can be captured. As Yin (1989: 23) points out, a case study "investigates a contemporary phenomenon in its real-life context" and is most suitable "when the boundaries between phenomenon and context are not clearly evident" and in situations "in which multiple sources of evidence are used."

3.2 Case study selection

A criterion for case study selection is that they have to complement each other and cover a broad range of cosmopolitanisation patterns. As Johnston *et al.* (1999: 206) argue, "each case should serve a unique purpose within the overall scope of enquiry. Each case must be chosen to complement others, e.g. because theoretically interesting pattern are expected." (quoted in Geels, 2002: 131).

The technology affordance is a first basis for my selection. Thus, case studies in the lower, middle and higher regions of the technological hierarchy are necessary. In addition, I will make sure that there is also variation with regard to the affordances shaped by actor-constellations and the historical setting. Therefore, I will start with a case study on the level of materials and continue with a contrasting second case study on the same level, but with a different affordance in terms of actor-constellation and historical setting. Next, I will move up a level in the technological hierarchy and do a case study on an artefact. Finally, I will present an "extreme case" which is located in the top of the technological hierarchy, in order to assess whether cosmopolitanisation as I conceptualised it, is also valid for the highest level.

Since my specification of cosmopolitanisation is tentative, I will use the first case study also as a "proof of existence". The first case study, therefore, will be the most comprehensive and detailed. In order to function as a "reality check" of my conceptualisation, it has to give a convincing account of cosmopolitanisation — i.e. circulation and aggregation, emergence of infrastructures and a local-cosmopolitan division of labour. For that reason, I will study a case of cosmopolitanisation which originated in the second part of the nineteenth century — when the world was not as filled with cosmopolitan elements as it is today, so that the basic dynamics of the cosmopolitanisation process are visible as such.

3.2.1 First case study: reinforced concrete

Reinforced concrete emerged in the second half of the nineteenth century and by the First World War is had evolved into an accepted, fairly reliable, somewhat calculable and regulated construction technology.

> "The rapid acceptance of reinforced concrete as a construction material between 1890 and 1914 is one of the most striking developments in the history of building technology. What makes this pioneering era so interesting is that concrete structures spread world-wide and yet, as S. B. Hamilton notes, the material was "deeply mysterious in its basis of design." Not only was there little reliable information regarding its use, but it was sold mainly in the form of proprietary systems, and patentees resisted revealing their calculations. Despite the uncertainties, however, investors took the plunge, and within a short period reinforced concrete structures went up around the globe. And some collapsed, too." (Wermiel, 2002).

Clearly, reinforced concrete is an interesting case to start my empirical research on cosmopolitanisation. It started out as a heterogeneous set of local technologies and evolved into a cosmopolitanised technology in the twentieth century. It meets the criteria I put forward in the previous section: it is a technology on the level of materials; it originates in the nineteenth century (while it stretches well into the twentieth century) in a context which was not filled with (generic) cosmopolitan elements — although there were professional civil and hydraulic engineering communities. With regard to the technology affordance, the material was "deeply mysterious in its basis of design", and it must have been a challenge to achieve reliable performances across time and space, also because the circumstances under which reinforced concrete structures were built were highly variable. The impenetrable nature of reinforced concrete structures would have made secrecy a productive appropriation strategy and knowledge transfer largely relied on face-to-face interactions. At the same time, the basic idea was simple enough to be tried by many practitioners. Given the low level of complexity, few alignments with other (complementary) producers were required, which would have allowed for local variants to emerge side by side. As a constructive material, there is a risk of collapse, which might have created an affordance. Reinforced concrete emerged in a context shaped by civil and hydraulic engineering regimes. As a new material, it had to find a place for itself in such higher level regimes. Cosmopolitanisation of reinforced concrete is likely to be shaped by pressures from existing building and construction regimes. Thus, reinforced concrete emerged in a constellation characterised by many small contractors, architects, civil and hydraulic engineers working for large professional customers (including governmental agencies), various large and small potential customers, building inspectorates, testing stations, and engineering societies. It is to be expected that engineering societies, testing stations, and other intermediary actors play an important role in eventual cosmopolitanisation of reinforced concrete. The presence of large professional customers might also play an important role in the production of cosmopolitan knowledge in this case.

3.2.2 Second case study: paint

I selected paint technology as a contrasting case study. While it is also on the level of materials and covers more ore less the same period as reinforced concrete, cosmopolitanisation of paint technology was much slower and less comprehensive than in the case of reinforced concrete. Paint formulation is an age-old technology which has evolved from an art into a formulation practice which is still characterised by much experiential know-how but nowadays is complemented with insights in underlying physico-chemical processes. The formulation process was enigmatic and based on trial-and-error learning rather than a grasp of the processes at work. As in the case with reinforced concrete, it must have been a major challenge for formulators to achieve a required performance in view of the variable nature of raw materials and the variable application conditions. Unlike reinforced concrete, paint did not have to be formulated on location, which would have allowed for a better control of formulation circumstances. The impenetrable nature of paint formulation allowed for secrecy as a means of appropriation, and given the low level of complexity, few alignments with other (complementary) producers were required, so that many local variants existed. Possibilities for mass-production were limited by distribution cost, limited storage life and heterogeneous applications of paint (which made the idea of a "universal" paint improbable). A key difference with reinforced concrete is that the level of risk is much lower. Finally, because paint does not play a constructive role in higher level configurations, few affordances can be expected on account of existing technological regimes. Thus, there would be few technological affordances for cosmopolitanisation.

The actor constellation can also be expected to have created few affordances. When paint formulation became a distinct part of the value chain at the end of the nineteenth century (that is where I will start my case study), there were many small regional formulators who bought their natural ingredients from a variety of suppliers (who supplied to other industries as well). During the twentieth century a supplier-dependent innovation pattern emerged in which large chemical companies became suppliers of synthetic materials. In the same period, large industrial customers emerged (e.g. automobile industry) which required high-performance coatings. It will be interesting to find out how these shifts in affordance structures affected cosmopolitanisation processes.

3.2.3 Third case study: video tape and video-cassette recording

I selected the case of video-tape and video-cassette recording as being situated on a higher level in the technological hierarchy which creates a different affordance structure. Videorecorders are sophisticated artefacts, produced by large high-tech electronics companies. The video-cassette recorder (VCR) has been studied widely for the standardisation battles that occurred. In these studies, the existence of network externalities has been stressed. Such externalities create expectations about “first mover advantages” which lead to the emergence of a “race” and a “battle of the standards” between rivals with different configurations (“formats”). In my case study, however, I am not so much interested in explaining how the battle was won, but in how a collective knowledge reservoir was built-up at a cosmopolitan level. In fact, the standardisation battle was the final act in a long history, in which technological knowledge was produced by various competing and collaborating electronics firms and research centres, and in which actors built on each others’ advances. A related and notable aspect of this case study is the role of patenting and cross-licensing practices and the formation of alliances. I will examine how this was related to the achievement of translocality. The VCR descended from the professional (broadcasting) video-tape recorder (VTR) which was introduced in the 1950s, and I will pick up the story from there.

An interesting element in the story of video recording is how rivals were able to reverse engineer their rivals’ artefacts. Another difference with the previous two case studies is that the level of complexity is higher, which implies that producers have to create alignments with (complementary) producers and suppliers. A VTR/VCR is an assemblage of designed components which have to interoperate. In case of videorecording, a special type of interoperability between recordings and recorders (of the same format) was required. This creates an affordance to produce knowledge which can be shared, at least between members of a project or alliance. Typical for a many artefacts, videorecorders are made within factories and are then shipped to customers. This creates an affordance for making configurations robust, so that they can operate reliably in a wide variety of contexts. At the same time, the application contexts were prestructured since television studios and, later, living rooms are rather uniform across the globe — notwithstanding different television standards in Europe, America and Japan — which made it relatively easy to anticipate on user contexts. This mobility of videorecorders allowed for economies of scale, which further contributed to an affordance for the development of robust knowledge. The level of risk and uncertainty was relatively low. While failure of professional videorecorders would have been a problem for broadcasters, this could be taken up by having broadcasters' experiences as a valuable feedback to improve the technology. A major affordance was that videorecorders were part of an overarching television and broadcasting regime. This regime was already cosmopolitanised, and engineers working on video recording could draw from collective knowledge reservoirs.

Video recording is a typical example of a R&D-dependent innovation pattern. The actor constellation in the early 1950s was characterised by a few large electronics companies and a number of small innovative firms. Dominant players can be expected to take the lead in the production of collective goods. The presence of several large broadcasters with a keen interest in a reliable and flexible video-recording technology, created an affordance for cosmopolitanisation. There also were some specialised suppliers, in particular with regard to tape manufacture. In addition, the presence of engineering societies and industry associations shapes cosmopolitanisation. From the outset, there were infrastructures for circulation and aggregation. In other words, video recording emerged in a context which was highly cosmopolitanised already. Thus, the contrast with the cases of reinforced concrete and paint also resides in the difference in historical setting. An added element is that videorecording emerged after the Second World War, a period in which industrial R&D was recognised as important.

3.2.4 Fourth case study: air traffic control

I selected air traffic control as an extreme case, located in the top of the technological hierarchy. The creation of a configuration that works involves a different kind of knowledge than in the previous cases. As Hughes (1998) has argued, managerial knowledge is as important as engineering knowledge in case of complex technical systems. The technological affordances are shaped by the fact that subsystems have to interoperate in one overall architecture. There are aircraft flying from one location to another, which creates interoperability requirements with adjacent air traffic control systems. The notion of air traffic control emerged after the First World War when air traffic increased. As a "second order" system, the development of air traffic control technology is closely related to developments in the "first order" system of air traffic. The introduction of jet aircraft, for instance, called for major changes in air traffic control systems. What started out as a loosely coupled patchwork of systems gradually evolved into an integrated architecture that now spans the globe.

Failure of air traffic control systems can have fatal consequences (as is demonstrated by several major accidents). This affordance shaped knowledge production at all levels of the technological hierarchy: only reliable technologies were allowed to be included in the air traffic control system. The life-span of air traffic control systems is long: once it is implemented, it is costly (and risky) to change or upgrade it, in particular because systems cannot be switched off temporarily. This calls for a planned, coordinated approach, not only within national systems, but also on an international scale. As air traffic systems grew more complex, this interoperability affordance increased.

Clearly, this is an extreme case where many dynamics play a role, and cosmopolitanisation of technological knowledge may well be part of larger concerns about reliable architectures. This adds a further layer to what Hobday (1998) has identified as characteristics of complex products and systems (cf. section 2.3.3). It will be interesting to find out if, and how, cosmopolitanisation processes evolved given the highly complex nature of air traffic control systems and the extent of socio-political shaping of the technology. On the one hand, strong interoperability and reliability requirements work on the configuration, which stimulate cosmopolitanisation. On the other hand, as Davies and Brady (2000) argue, the specificity of complex systems makes it difficult to learn from one project to another, let alone to share this knowledge with other actors.

3.3 Case study protocol and data collection

What kind of information must be collected in the case studies? First, cosmopolitanisation patterns need to be traced. Cosmopolitanisation, as I specified it, covers the circulation and aggregation activities, the emergence of local-cosmopolitan divisions of labour, and the emergence of infrastructures. Thus, I need to describe how actors start to produce translocal knowledge which is not tied to specific local needs, but refers to technology as such. Examples of translocal knowledge products include handbooks, articles in journals, papers presented at conferences, standards, technical models (Disco *et al.*, 1992), widely shared rules of thumb, guiding recipes, rules of calculation, and regulations with regard to how a configuration should be made. There are many potential knowledge producers: producers of products or services, complementary producers, suppliers, customers, as well as regulatory actors, university departments, and a range of intermediary actors like consulting engineering firms, sectoral research centres, committees, knowledge transfer centres, organised research programmes and standardisation organisations. The emergence of forums like journals, conferences, trade shows, industry exhibitions, consortia, and standardisation committees also needs to be mapped.

Second, the affordance structure has to be traced, in order to analyse its effects on cosmopolitanisation patterns. This means that the historical setting and existing mosaics of technological regimes have to be analysed in terms of their contribution to an affordance structure. Secular changes have to be mapped as well, as these are likely to influence the affordance structure.

Also technological aspects have to be analysed in terms of their contribution to an affordance structure: how do position in technological hierarchy, degree of impenetrability, interoperability requirements, level of complexity, associated risks and uncertainties, potentials for mobility (and scale) affect the affordance structure? Subsequently, the actor-constellation has to be analysed in terms of its role in the affordance structure. What are the interdependencies between different actors? Are there dominant parties? Are there demanding parties? How do changes in actor-constellations, e.g. the emergence of intermediary actors, affect the affordance structure?

How to collect the information that is needed to analyse cosmopolitanisation patterns (or plots) in case studies spanning several decades? An important source will be secondary literature in which technological and industrial developments in the relevant domains are described. Developments in technology and the actor constellation can be identified on this basis and cross-checked by using a variety of sources. Information on the emergence of intermediary actors and forums can also be found in secondary material. Sometimes indications can be found on the occurrence of circulation and aggregation activities. Since most secondary sources are not geared to my specific interest in cosmopolitanisation, I have when feasible also used primary sources like contemporary journals, conference proceedings, reports, handbooks, and standards. These will be seen as reflecting outcomes of circulation and aggregation activities, but also show up processes and debates. Several intermediary actors (like professional societies and industrial associations) have published historical information on themselves, now also on the Internet. Although this information has to be treated with care, it offers additional data.

The data will thus be heterogeneous, and analysis will have the form of creating a plausible story. Van Lente (1993) has argued that the analyst can stop adding complexity when a convincing story, with a plausible plot can be told. This plot is "neither something that is only imposed by the analyst to mould the 'raw material' into a story, nor is it something that is 'out there' in the real world, and is just reflected in the story of the analyst." (179-180). In a sense, case studies are narrative reconstructions of patterns in reality which are themselves narratively shaped (in a broad sense).[1] When comparing case studies, the analyst should "look where the storylines overlapped, to look for common themes and recurring events." (Van Lente, 1993: 181).

My case study protocol contains three basic elements. First, I will establish a main chronology and identify actor constellations and changes in technology. Second, I will use secondary sources and some primary sources to reconstruct dynamics, paying special attention to cosmopolitanisation processes and shifts and developments in actor constellation and technology. Finally, different phases in cosmopolitanisation will be identified and characterised. On this basis

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[1] See Deuten and Rip (2000) where a reconstruction of the narrative shaping of a product creation process is made. Such narrative shaping is multi-authored, and humans as well as non-humans tell stories which influence further/other stories. We used the notion of an emerging 'narrative infrastructure' to analyse the overall effect of interacting stories. Analytically, the important point about infrastructures is that they help to explain how coherence and linearity can emerge in multi-actor, multi-level processes, without any one actor specifically being responsible for it. Product creation processes are one example of emerging coherence. They might well be a specific genre with a typical form of narrative infrastructure.

I will create a storyline in which cosmopolitanisation is rendered in its interaction with an evolving affordance structure.

Chapter 4.
Reinforced concrete

4.1 Introduction

> "The rapid acceptance of reinforced concrete as a construction material between 1890 and 1914 is one of the most striking developments in the history of building technology. What makes this pioneering era so interesting is that concrete structures spread worldwide and yet, as S. B. Hamilton notes, the material was "deeply mysterious in its basis of design." Not only was there little reliable information regarding its use, but it was sold mainly in the form of proprietary systems, and patentees resisted revealing their calculations. Despite the uncertainties, however, investors took the plunge, and within a short period reinforced concrete structures went up around the globe. And some collapsed, too." (Wermiel, 2002)

This quotation illustrates how reinforced concrete started out as a "deeply mysterious" technology, on which little reliable knowledge was available. Around 1890 it was very much a local technology, without a collective knowledge reservoir. Indeed, patentees resisted to reveal knowledge on their proprietary systems. In the twentieth century, reinforced concrete became a cosmopolitan technology with an institutionalised knowledge base, a local-cosmopolitan division of labour, and an elaborate infrastructure for circulation and aggregation. How did this happen, and how can it be understood? What was the role of affordances created by technological aspects, an evolving actor-constellation, and existing regimes and historical setting?

The case study of reinforced concrete will be presented in two parts. First, I will present how reinforced concrete emerged in France and elsewhere in Europe, how it started out as a material which was hardly understood and impossible to calculate, and how it established itself as a reliable, calculable and acceptable technology. This part ends when reinforced concrete becomes standardised and incorporated in building codes in the first decade of the twentieth century in several European countries. I will then shift the focus to cosmopolitanisation processes in the Netherlands. Dutch contractors and engineers were not among the pioneers, but quickly mastered the new technology, and became knowledge producers themselves after 1900. The Dutch part of the case study thus begins with a period of knowledge transfer from surrounding countries — which had become possible thanks to partial cosmopolitanisation elsewhere — and then proceeds with cosmopolitanisation processes.

4.2 From local to cosmopolitan: early developments in reinforced concrete, 1850-1900

4.2.1 A novel combination of concrete and iron

Disco (1990: 274-5) remarks that

> "[i]t is unlikely that early efforts to combine iron and cement mortar into a monolithic structure were motivated by a clear perception of the possibilities which later proved to inhere in the technology. Rather, they must be seen as inspired local solutions to specific problems. No doubt many of the earliest instances of the use of wrought iron/cement structures never made it into the contemporary collective consciousness and hence contributed nothing to what was later to become the cosmopolitan technology of reinforced concrete. Direct witnesses probably perceived nothing particularly noteworthy in such structures, viewing them as no more than clever solutions to particular problems rather than as pregnant adumbrations of an entirely new constructive technology."

Thus, what is now commonly known as reinforced concrete technology, started out as a heterogeneous set of local solutions for specific problems. The "inspired local solutions to specific problems" emerged in a context where cement and iron had become increasingly available as relatively cheap and uniform materials.[1] In the early nineteenth century, natural cements, such as lime mortar, which was made of lime, sand and water, were gradually replaced with higher-strength artificial cements. The first artificial cement, so-called Portland cement, was patented by Joseph Aspdin in 1824. In the following years the quality of cement was further improved, for instance by increasing the temperature during the manufacturing process. In the second half of the nineteenth century, cement gradually became cheaper, more uniform and reliable. Plain concrete, made by adding to cement an aggregate (sand, gravel, powdered brick and/or pebbles) and water, was chiefly used for walls, since it was very good at resisting pressure. Sometimes concrete was also used to replace brick in floor arches in constructions such as iron-framed factories. Also precast concrete blocks, artificial stones, were produced as substitutes for bricks. Experiments were done with concrete pipes, reservoirs and ground tanks, tiles, floors, and concrete blocks to be used in the construction of harbours. But concrete was also brittle, and therefore not good at resisting tensile stresses, for instance, in floors slabs. Cracking was an all too common problem.

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[1] A more detailed discussion on the history of concrete can be found in Scharroo (1946).

Iron and its production process had also been improved.[2] In the nineteenth century, steel could be produced which exhibited great strength, hardness and other valuable mechanical properties. The availability of low-cost steel in Britain and the United States soon revolutionised building construction and provided steel to replace iron in railroad rails and many other uses. For civil engineers, steel became an ideal construction material because of its great strength. They developed methods of calculation that increased their command of steel constructions. Their mastery over steel construction became part of their identity as professional engineers. Iron and steel set a standard that was hard to meet by other constructional materials.

Novel combinations of iron/steel and cement/concrete were tried, in response to problems with traditional building materials. Wood, for instance, was a much-used building material, but is was rot-susceptible and not very durable in wet conditions. In the 1840s, the Frenchman Joseph-Louis Lambot tried to find a solution for the problem that his wooden flower pots and water tubs were not durable. Like other contemporaries he experimented with concrete flower pots. Concrete, however, tended to crack. He solved this problem by embedding pieces of iron in the concrete pots. He eventually came to realise that he had invented a new material, which he called *ferciment*.[3] His *ferciment* pots and tubs were waterproof, strong, and not too heavy to be immovable because they could be made relatively thin. Building on these experiences, he constructed a rowing boat made of *ferciment* in 1849, which he exhibited at the first World Exhibition in 1854.[4] Lambot took out patents in France and Belgium one year later, in which he stated that his invention was meant to replace wood in shipbuilding, and in general where wood had to be water resistant. By combining iron and concrete, iron reinforcement prevented cracking of concrete structures, while concrete protected iron from rusting. His *ferciment* seems to have attracted little attention, however, and its application remained limited (Elliot, 1992).

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[2] The blast furnace, which produced pig iron, had been introduced in Europe in the fifteenth century. Later, a two-stage production process was introduced in which cast (pig) iron was converted to wrought iron. Pieces of cast iron were placed on a finery hearth, on which charcoal was being burned with a plentiful supply of air, so that carbon in the iron was removed by oxidation, leaving semisolid malleable iron behind. As a result of increased iron production in the sixteenth century in England, wood for charcoal had become scarce and was replaced by coal in the form of coke. Steam engines made it possible to provide blast furnaces with more air. The production process was further accelerated with the introduction of the puddling furnace in 1784 and the hot-blast stove in 1828. Further innovations made it possible that furnaces could operate at temperatures high enough to melt iron. In 1856, Henry Bessemer patented his converter process for blowing air through molten pig iron which further increased the quality of steel and enabled mass-production. The Bessemer converter was adapted in the late 1870s for use with phosphoric pig iron which was abundant on the continent of Europe. Later, the open hearth furnace, which was introduced in the early 1860s, outstripped the Bessemer converter and become the dominant steel making process.

[3] Translation: ferrocement or ironcement.

[4] During the second half of the nineteenth century and the early twentieth century, various ships would be made of concrete and iron, but eventually this application was abandoned.

Another well-known problem with conventional building materials such as wood and iron was their poor fire-resistance. Economical and fire-resistant forms of construction were widely sought as a solution to the fatal and costly fires that frequently consumed mills, warehouses and public buildings (Bussell, 1996). In 1852 the French builder François Coignet, motivated by this demand for fireproof buildings, made a building by encasing an iron skeleton in concrete. Iron embedded in concrete was claimed to be less vulnerable for high heats. Coignet called his use of concrete and iron *béton aggloméré*, later also known as *Béton Coignet* (Tédesco, 1906). Coignet exhibited his new technique at exhibitions, including the World Exhibition in Paris of 1855. He apparently saw a bright future for *béton aggloméré* as he predicted that "[t]he reign of stone in building construction seems to have come to an end. Cement, concrete and iron are destined to replace it." (Newby, 1996: 266). Whereas in Lambot's *ferciment* concrete was the main material that was supported by iron wires and bars, in Coignet's *béton aggloméré* iron beams were the main material protected by concrete. Nine years after his first buildings in *béton aggloméré*, Coignet seems to have sensed new possibilities, in which concrete played a more constructive role. He described in his handbook *Bétons aggloméré appliqué à l'art de construire* (Coignet, 1861) a method to construct concrete (i.e. fireproof) floors in which concrete slabs were reinforced with small iron beams to prevent cracking. In the same year he founded a company called *Société Centrale des Bétons Aggloméré, système Coignet* to exploit his *système*. As an example, he built his own all-concrete house in Paris as a showcase in which the roofs and floors were reinforced with small wrought iron I beams. His company enjoyed commercial successes and brought about the first substantial use of concrete in buildings in France in the period 1850-1870 (Kuipers, 1987).

To attract attention to their inventions, the inventors disclosed part of their knowledge (e.g. through exhibitions, patents and handbooks), but this knowledge was rudimentary and tied to specific solutions, and did little to elucidate the "mysteriousness".

The search for new construction methods occurred in other countries as well. In Britain, the inventor and entrepreneur William Boutland Wilkinson tried to make fireproof all-concrete buildings. Wilkinson faced the problem of how to construct concrete floor slabs that would not crack. In his eventual solution he gave concrete and iron complementary roles, which was innovative, since others before him had supplemented a main material by an auxiliary material. In 1854 he patented his method for embedding wire ropes or hoop iron into concrete elements. In his patent he described that the iron reinforcement should take the tensile stresses, and concrete the compressive stresses (Elliot, 1992). This was one of the first descriptions of an operational principle of concrete-iron, but it received little attention.

The Frenchman Joseph Monier was more successful in attracting attention for his combination of concrete and iron, and on the basis of a clever patenting strategy, he became an important player in the early years of reinforced concrete. Independently of Lambot, Coignet, or Wilkinson, he had been looking for ways to replace wood with a material that was more durable. As a commercial gardener, he experimented with large concrete flower pots and water tubs. To prevent cracking, he added iron-wire reinforcements. His method proved to work satisfactorily, and in 1867 he took out a patent. In the same year he exhibited his invention at the Paris Exposition where his large flower pots, tubs and basins attracted a lot of attention. Monier soon realised that his invention did not have to remain limited to waterproof artefacts. In subsequent years, he extended the application of his "Monier system" to other engineering structures, such as pipes and reservoirs (patented in 1868), flat slabs (1869), bridges and footbridges (1873) stairs (1875), and floor constructions (1878). Typical for the Monier system were concrete slabs, reinforced with a network of thin round iron bars, resting on load bearing walls. After he took a universal patent in 1878, he sold licenses to constructors in Germany, Austria, England and Belgium. His system became successful, and Monier came to be recognised as "the inventor" of reinforced concrete.

Monier was an autodidact and his system was "backed up neither by theory nor by systematic experiment." (Elliot, 1992: 172).[5] With the benefit of hindsight, it can be inferred from the way he positioned the iron reinforcements in his early patents that Monier did not appreciate the complementary roles of concrete and iron, where concrete took most of the compressive forces, and the embedded metal wire took most of the tensile stresses. In his early patents he placed the iron reinforcement in the middle of beams or slabs, rather than in the regions where the tensile forces are most prominent, i.e. in the bottom part of a beam or slab. By the time of his later patents he had come to appreciate this as he positioned the iron in those regions. It is illustrative for the way knowledge on reinforced concrete was produced: based on trial-and-error and "constructional sense", rather than guided by theoretical insights. Given the local character of this experiential knowledge, it was transferred to licensees by sending French experts.

Monier built many constructions in France, including several impressive bridges, which clearly demonstrated what the new material was capable of. Heavy-load tests were performed to show the strength of the constructions. However, these tests could not demonstrate the durability, and this would remain an issue for the next decades. Minute cracks in the concrete could lead to rusting of the embedded iron, which could result in collapses. Indeed, it was not uncommon that constructions did collapse, which gave ammunition for sceptics that the technology was inherently unreliable. Despite these uncertainties, it did not prevent venturing customers to "take the plunge" as the advantages of

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[5] Monier's lack of theoretical understanding of his material would not affect his fame. M. Förster in his authoritative *Entwicklungsgeschichte und Theorie des Eisenbetons* (Emperger and Förster, 1912: 18; 2nd ed.), for instance, wrote: "Wenn es somit Monier () nicht gegeben war, den statischen und wirtschaftlichen Wert seiner Erfindung zu schätzen and auszunutzen, so gebührt ihm doch der unbestrittene Ruhm, durch eine ungemeine praktischen Blick alle die Vorbedingungen geschaffen zu haben, welche den späteren Siegeszug des Eisenbetonbaues vorbereiteten."

reinforced concrete in terms of cost, fire-resistance and shock-proofness were alluring. In the period from 1867 until the 1890s, when the last of Monier's patents expired, a large majority of the reinforced concrete structures which were built (mainly in niche markets) was based on the Monier system. As more and more structures were built, experience accumulated, and reinforced-concrete contractors became increasingly experienced.

4.2.2 Practical and theoretical advances in Germany

Monier's universal patent was bought in Germany and Austria by an ambitious German constructor, Gustav Adolf Wayss. He not only applied the Monier system, but also created and published new knowledge on the operational principle of reinforced concrete. He had a keen eye for the commercial possibilities of reinforced concrete, or *Eisenbeton* as it came to be known in Germany. By dedicating himself completely to the Monier system, he linked his commercial fate with the technological fate of reinforced concrete. As Wayss tried to apply *Eisenbeton* in buildings he had to deal with the relatively strict building regulations in Germany. The authorities could not easily be convinced of the reliability and durability of *Eisenbeton*. There was no way to make reliable calculations of the strength of *Eisenbeton* constructions, which was an additional problem. In an effort to get permission from the authorities, Wayss performed an extensive testing programme which was carried out under supervision of French experts.

Regierungsbaumeister Mathias Koenen was appointed by the Prussian government to observe these tests. He was in particular concerned with the reliability and durability of the new material. Rusting of the iron reinforcements was a potential problem that could be caused by shearing and cracking. When tests showed that the expansion coefficients of iron and concrete were practically the same, he came to appreciate that concrete and iron could act as a unity. His understanding of *Eisenbeton* was further enhanced when he hit upon Thaddeus Hyatt's earlier, but poorly publicised, experimental findings (Disco, 1990)

Hyatt had been an American consul in France and had taken notice of the innovative developments in construction materials by Coignet and Monier. In the early 1860s, after he had returned to England, he performed a series of experiments on concrete beams and floor slabs reinforced with iron. He acquired information about the possibilities and characteristics of the new construction material. Somehow, he did not publish his experimental findings until 1877, ten years after Monier's first patent. In *An account of some experiments with Portland cement concrete combined with iron, as a building material, with reference to economy of metal in construction, and for security against fire in the making of roofs, floors, and walking surfaces* he described many characteristics and properties of concrete reinforced with iron. For one thing, he determined that the heat expansion coefficients of concrete and iron were practically the same, which meant that both materials could act in a unity as a composite material. His experiments proved the fire-resistant qualities of reinforced concrete constructions. In order to prevent shearing, he propagated the use of a 'deformed bar' rather than Monier's plain round bars. Hyatt's advanced ideas received little attention at the time, due to limited circulation of his privately published paper (Disco, 1990). Moreover, he failed to find investors, and patent infringements eliminated his opportunities to exploit his findings successfully (Elliot, 1992).

Koenen, witch his theoretical background, appreciated Hyatt's findings, and he started to formulate general principles for the static calculation of simple constructions. In 1886, in an attempt to give *Eisenbeton* credibility, he published his rudimentary *Eisenbeton* theory in the *Zentralblat der Bauverwaltung*, a widely read journal on building management. The Building Police in Berlin seems to have been convinced by his theoretical treatment (and the extensive testing) since they subsequently approved the use of *Eisenbeton* within city limits. Thus, Prussian requirements, and a need to give reinforced concrete credibility, induced a theoretical-experimental project which would soon become international and would last for decades.

The ambitious entrepreneur Wayss understood that in order to be successful, he needed to disclose part of the knowledge on reinforced concrete. He was very keen on showing the Monier system to the building world. He used a whole arsenal of instruments to promote his new technology, like lectures, press releases, advertisements, and remarkable entries for expositions. He built a number of elegant footbridges between 1886 and 1890 for the sole purpose of showing off the new possibilities of reinforced concrete.[6] But demonstrations alone were not enough, given the impenetrable characteristics of finished structures and the requirements in building regulations. In 1887, in collaboration with Koenen, he published a résumé of Monier technology as it had been developed and applied up to that time. His so-called *Monierbroschüre*, *Das System Monier (Eisengerippe mit Cementumhüllung) in seiner Anwendung auf das gesamte Bauwesen*,[7] contained theoretical reflections on the calculation of reinforced concrete structures, results of Wayss' tests, and a review of actual Monier projects (Disco, 1990). Wayss financed the Monier brochure himself and put it into wide circulation in an attempt to gain acceptance within the building sector. It became an influential book on reinforced concrete construction and provided an important stepping stone towards the production of translocal knowledge. Although it was primarily written to create acceptance, and thus a market, it became a valuable and influential guidance for other Monier licensees as well as supervisors and inspectorates in Germany, and also elsewhere after it was translated into other languages (Elliot, 1992). Thus, the *Monierbroschüre* was an aggregation product that, through wide circulation, influenced many local practices. Whereas Monier had enjoyed commercial success without much understanding,

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[6] In practice, however, he usually made his constructions less elegant and much heavier than technologically necessary. The designs of *Eisenbeton* bridges, for example, mostly had forms that were based upon conventional designs in stonework in order to receive permission by the authorities — which shows how the existing building regime influenced the development of reinforced concrete (Billington, 1989: 2)

[7] Translation: Monier Brochure, the system Monier (iron framework with cement covering) in its application for the entire building trade.

Wayss and Koenen developed a better understanding of the Monier system, based on experience, theoretical exercises and testing.

4.2.3 The era of proprietary systems

Based on his patenting strategy, Monier's system became the dominating form of application of reinforced concrete in Europe in the 1880s and 1890s. Monier was practically a synonym for reinforced concrete on the European Continent.[8] At the same time, many new systems, which to a greater or lesser degree deviated from the Monier system, were developed and patented. As a result, many new varieties of reinforced concrete were introduced, which increased the "fluidity" of the situation for contractors, customers as well as inspectorates. The systems, which were usually named after their inventors, used different names for reinforced concrete, such as ferro-concrete, ferro-cement, armoured concrete, cement-iron, concrete-iron, etc. On his tour of Europe, the American L. Colby identified no less than 144 systems, most of them protected by patents (Colby, 1909).[9] The introduction of many different systems resulted in a vehement "battle of the systems" which lasted until the first decade of the twentieth century. A contemporary reinforced-concrete contractor in the Netherlands, L.A. Sanders, characterised the situation as a "hunt for patents", and he criticised one of the most successful entrepreneurs, François Hennebique, for "veiling himself in a cloud of patents" and for overemphasising and exaggerating his innovativeness. He was "above all a competent merchant" rather than a technological innovator (Sanders, 1907). Patents played a crucial role in the appropriation as well as promotion of the systems. This fluidity did not contribute to a better insight in the merits and demerits of the new technology. Rivalry between system owners was high, and they kept their knowledge and tricks of the trade secret. With limited interchange of experiences, and limited circulation, knowledge remained largely system-specific. Technical details were not shared with rivals,[10] and patents were protected with vigorous litigation (Cusack, 1987). System owners tended to emphasise their systems' uniqueness, rather than to point at similarities. Each system used different mixtures of concrete, and iron reinforcements were positioned and shaped differently. Methods of calculation also diverged considerably. Some systems were very difficult to calculate. Cottancin's system, for instance, arranged beams, or ribs, crossing the platforms or

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[8] In the Netherlands, for instance, reinforced concrete structures were often indicated with the name *Monierwerken* and *Monier-ijzer* in the late nineteenth century (Van Erkel, 1900).

[9] The book *Reinforced Concrete in Europe* of 1909, authored by the American L. Colby, is referred to by Winter (1982).

[10] Dicke (1967) has a telling anecdote on the level of secrecy in the Netherlands. In 1900 it was commonly thought that only with a mysterious hardening powder the mixture of cement, sand, gravel, and water would harden into concrete. Practically nothing was known about the determination and calculation of forces acting on a beam or slab. A little table with the coefficients for the determination of the girth of the iron bars and the amount of reinforcement was a very valuable piece of paper that was put away in a safe at the end of the day.

slabs of a floor system in diagonal directions, which was good from an aesthetic and constructional point of view, but did not lend itself to easy calculation (Tédesco, 1906). Some systems were designed only for specific structural elements, such as floors and pipes, while others were adapted to complete building frames (Cusack, 1987).

Among the many systems, Hennebique's system became one of the most successful. After he had seen Monier's tubs and tanks at the Paris Exposition of 1867, Hennebique began to search for new ways to apply this new material to building construction. He developed a keen insight in the possibilities of reinforced concrete construction, based on numerous experiments with reinforced concrete which he performed for more than a decade. In 1879 he discovered, for example, that floor slabs could be made stronger if the rods were bent upward at the ends. He progressed to a complete building system, patented in 1892. A key element of the Hennebique system was that columns, beams, joists, and floors formed one *monolithic* whole. This was new, since the Monier system used discrete elements which were assembled on location. The Hennebique system used for reinforcement plain round steel bars with fish-tailed ends and stirrups of flat strips. The Monier system was characterised by a more finely distributed and symmetrical network of thinner rods. Hennebique called his material *béton armé* to distinguish it from other names such as *ferciment* and *béton aggloméré*. Disco (1990) describes how a controversy emerged around

> "the question whether "monolithicity" had always been implicit in the Monier system (in which case Hennebique could only be regarded as a mere exegete of Monier and technological authority would have to be accorded to the latter and his adherents) or whether the monolithic style was in fact Hennebique's very original brainchild (in which case Monier adherents would have to acknowledge indebtedness to the Hennebiqueans for the breakthrough which had made reinforced concrete a universally practical building material and to define themselves as competent reinforced concrete builders only to the extent they had succeeded in appropriating the insights of Hennebique and his followers). Although the distinctions may seem minor, the vehemence with which the "battle of the systems" was carried on betrayed how much was at stake in this paternity suit." (Disco, 1990: 292, fn. 51).

A key to Hennebique's commercial success was that he established a consulting engineering firm to exploit his innovation after he had taken out a patent in 1892. His company, the *Maison Hennebique*, had a central office in Paris and appointed agents in different parts of the world. The central office had to approve all designs and calculations made by concessionaires, because quality control was of utmost importance to Hennebique in order to protect the reputation of his system. *Maison Hennebique* explicitly based its reputation on what it built and on the tests these constructions survived.[11] He promoted his system

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[11] Exemplary is Hennebique's bridge at Chatellerault. It was over 150 m long and had a centre span of 55 m. The firm's offices in Paris, built in 1898 were also an effective advertisement for the use of reinforced concrete. It showed the economy of building in *béton armé* because the walls and floors could be made

by bringing his innovative constructions to international forums such as the World Exhibition of 1900 in Paris.[12] Unlike Wayss and Koenen, Hennebique did not involve himself in a theoretical-experimental project. Like most of his rivals, Hennebique was an autodidact who lacked adequate scientific training and skills to analyse or calculate the behaviour of a composite material. Calculations of the Hennebique system were not backed-up by theory. *Maison Hennebique* did hire the Belgian engineer Paul Christophe to give technical and theoretical assistance (Lemoine, 1991).

Intra-organisational circulation and aggregation were important part of Hennebique's strategy. As part of his "knowledge management" approach, he organised special training courses for concessionaires and developed an infrastructure which included a journal and annual conferences. In 1898 the *Maison Hennebique* started publishing *Le Béton Armé*, a monthly journal that was part of the support network for licensees (Elliot, 1992). It consisted of two parts. One part, printed on white paper, was public and was used for articles that were considered to be of general interest, such as treatises on *béton armé*, descriptions of constructions, reports on experimentations, etc. The second part, printed on pink-coloured paper, was exclusively reserved for Hennebique's concessionaires. It was part of a private infrastructure for circulation within the world of *Maison Hennebique*. It contained articles on in-house experiences that could be shared within the 'Hennebique community'. Concessionaires used the pink pages in *Le Béton Armé* also to make inquires into solutions that had proven to be successful. In conferences of the *Maison Hennebique* the same dual approach was visible, with open and private meetings. This illustrates how Hennebique operated: in order to create and extend markets, one has to reveal some knowledge.

Thus, experiences with the Hennebique system were mobilised and aggregated within the multinational *Maison Hennebique*. In combination with a strict protection of its patents, this strategy worked very well and the *Maison Hennebique* became extraordinary successful. By 1900, the company was active in France, Belgium, England, Italy, and Austria. It had carried out over 3,000 projects, and averaged about 100 bridges per year (Elliot, 1992). By 1909, Hennebique had 62 offices, 43 of them in Europe, 12 in the United States, and the remainder in Africa and Asia (Cusack, 1987; Elliot, 1992). Through Hennebique's entrepreneurial activities, reinforced concrete was introduced in many parts of the world.

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much thinner which saved precious space. More storeys could be built while the height of the building remained the same. Economy was a major advantage, besides fire-resistance, waterproofness, hygiene, etc. Thus, his constructions were perhaps his strongest advertisement.

[12] The World Exhibition of Paris in 1900 exhibited graceful buildings by two leading contractors Hennebique and Coignet. Both contractors were awarded with a *Grand Prix*. The exhibition generated a lot of publicity for their building technologies. As a result, many new contractors entered the market (Tédesco, 1906). In the twentieth century, exhibitions and industry fairs became less important forums.

Although Hennebique was innovative in his use of monolithic structure, he largely built on conventional construction methods. The constructions, with solid columns, beams, and joists supporting short-span slabs, looked like wooden constructions. Thus, his frameworks were not strong visual expressions of the monolithic nature (Billington, 1989). This traditional approach did make calculations less complicated, however. Not until the 1910s were systems developed that eliminated the beams and joists, and new ways of design emerged that departed from tradition. With those innovative designs, the new composite material could be used in previously unimagined ways.

On a collective level, the battle of systems, and the corresponding fluidity and heterogeneity of the situation, did not contribute to a forthright acceptance and admissibility of reinforced concrete. For customers, the vast variety of systems in itself increased uncertainties. How to compare the pros and cons of different systems? Which method of calculation was most reliable? Customers that wanted to use reinforced concrete had to put their faith in reinforced concrete contractors and their idiosyncratic methods of calculation. Contractors had a "monopoly of expertise" and their knowledge was largely contextual, geared to specific applications and systems. Therefore, their knowledge and methods could not readily be extended to other systems. As long as the "race" had not been decided, reinforced concrete contractors had no incentive to share their knowledge. This situation was reinforced by the fact that they wanted to keep both the design and execution in their own hands. The execution of a design to a large extent determined the performance of a structure, and for reasons of liability, they could not delegate the execution. If, for example, formwork was removed too soon, constructions could become unreliable. Without regulations, the only way to make sure a design was sound, was to closely supervise the execution of the design.

Notwithstanding this impenetrability, several customers were prepared to accept the uncertainties and contract a reinforced concrete constructor. By 1900, thousands of structures, in a wide variety of forms, had been produced (Billington, 1989). As reinforced concrete was increasingly used in construction, customers, architects, civil engineers, regulators, and academics were challenged to have an opinion about the new construction technology. They were not insensitive to the advantages of reinforced concrete, such as economy, fire-resistance, waterproofness, flexibility, hygiene, and shockproofness. Thus, interdependencies between contractors, customers, architects and inspectorates increased.

Many architects were not enthusiastic about the new material, in the same vein as they had not been enthusiastic about iron constructions. They considered reinforced concrete as a material from the engineering world.[13] It did not

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[13] The professionalisation of civil engineers had intensified a battle of competence between architects and engineers. Traditionally, architects had been responsible for the design of private and public buildings,

accord with their aesthetic ideas, and they could not make the complicated calculations that were necessary to make good designs. As a result, the application of reinforced concrete in houses was limited.

The monopoly of expertise by contractors was also problematic for civil engineers working for public works departments and other large professional customers. They had to be able to take responsibility for the constructions they contracted out. In the view of professional engineers, comprehensible calculation methods that were based on extensive experimenting and testing according to scientific methods were required. They demanded a "rational application" of reinforced concrete, in which calculation could be backed-up by theory, and theory could be underpinned by sound experimental data. In the 1880s, Wayss and Koenen had already tried to create a wider professional and public interest in, and acceptance of, their reinforced concrete systems by inviting groups of architects, engineers and journalists to observe tests, by publishing brochures, by entering exhibitions, and/or by lecturing to professional bodies. In general, ambitious reinforced concrete contractors had to try to embed their new technology in an environment which at first was sceptical or just disinterested. Some contractors ventured into theory to satisfy sceptical architects and engineers, even if these theoretical exercises were still crude and rudimentary. As the number of contractors and interested customers increased, the contractors' monopoly of expertise became a increasingly untenable. Professional engineers, employed by large customers or building inspectorates, increasingly became active in the production and circulation of credible, credentialed technological knowledge, using existing infrastructures of journals, meetings and conferences. Contractors increasingly began to participate in a collective effort to create reliable knowledge — even though rivals would benefit from increased availability of knowledge. Reinforced concrete was too important to leave it to professional engineers who lacked practical expertise.

For both contractors and customers it became increasingly important to have a legal framework which could be referred to in case of conflict (e.g. when a structure collapsed, or when customers had "unrealistic" demands). Engineers employed by professional customers had to be able to take responsibility and regulations would help them to do this. Regulations would also give the market a signal that reinforced concrete was an acceptable technology. Since reliability and durability of the new technology had not yet been answered beyond any doubt, such reinsurance from an authoritative body would help convince sceptical or hesitant customers. To draw up regulations knowledge and expertise would have to be made available. Only if standards were based on aggregated experiences and theoretical insights backed up by experimental findings, these rules could provide credible guidance. For contractors, sound rules would pre-

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whereas civil engineers had been involved in industrial and commercial building and hydraulic works. Increasingly, with the introduction of new building materials such as iron and steel as well as reinforced concrete, architects saw their prerogative under attack. Increasingly, civil engineers started to make inroads in their domain.

vent that customers would draw up unnecessary or excessive requirements. On the other hand, it was also feared that rules could be a straightjacket for experienced contractors while it would give a misplaced sense of security to inexperienced contractors.

The question remained how rules and standards could be established in a sector that was characterised by many (often small) heterogeneous local practices. Without affordances, the collective good of standards based on consolidated knowledge would be difficult to achieve. At the same time, however, the affordance structure had evolved. In particular, the actor-constellation became characterised by demanding customers who were demanding reliable knowledge and were willing to take the initiative for collective action. The high level of variability and heterogeneity (in design, calculation, and execution), however, was something which would make the achievement of translocality precarious.

4.2.4 Cosmopolitanisation takes off

To create acceptance and a market, entrepreneurial contractors like Wayss, Coignet and Hennebique, had disclosed parts of their knowledge and expertise in the 1880s and 1890s. They had used existing knowledge infrastructures to bring their knowledge into circulation. Ambitious contractors, for example, wrote articles on reinforced concrete in journals that were read by potential customers, such as the journals of professional societies. Some of them gave lectures in meetings of professional societies, as members of these societies held influential positions in large customers (e.g. public works departments of large cities, army engineering corps, and railway companies) or inspectorates. For example, Edmond Coignet, a son of François Coignet who in 1861 had established the *Société Centrale des Bétons Aggloméré, système Coignet*, had shown a keen interest to participate in professional forums. In 1889, for instance, he had given a lecture to the *Société des Ingénieurs Civils de France* in which he explained the basic principle that iron reinforcement should be placed in the lower regions of a concrete member in flexure. He had also tried to ascertain the laws of resistance and deformation of reinforced concrete by performing numerous tests using scientific methods.

In the nineteenth century, many journals on civil engineering and architecture had been established in Europe, and in the 1890s articles on reinforced concrete began to be published in these journals.[14] This signalled an increase in circulation and aggregation activities, not only be contractors, but by profes-

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[14] For example: Journal du génie civil, des sciences et des arts; a l'usage des ingénieurs civiles (Paris, 1828); Annales des ponts et chaussées (Paris, 1831); Allgemeine Bauzeiting: mit Abbildungen für Architecten, Ingenieurs, Dekorateurs, Bauprofessionisten, Oekonomen, Bauunternehmer (Wien, 1836); Revue générale de l'architecture et des travaux publics: journal des architectes, des ingénieurs, des archéologues (Paris, 1840); Journal de l'architecture et des arts relatifs à la construction: revue des travaux exécutés en Belgique (Bruxelles, 1848); L'ingenieur (Paris, 1852); Zeitschrift des Vereines Deutscher Ingenieure (V.D.I.) (Düsseldorf, 1857); Zeitschrift des Österreichischen Ingenieur- und Architectenvereines (Wien, 1865); Deutsche Bauzeitung: Fachzeitschrift für Architectur and Bautechnik (Berlin, 1871).

sional engineers as well. As mentioned before, *Regierungsbaumeister* Koenen had published his findings and insights in 1886 in the *Centralblatt der Bauverwaltung*, an internationally read German journal of building management.[15] In 1890, this elicited a critical reaction by the Austrian engineer Paul Neumann in the widely read journal of the Austrian engineering society, the *Wochenschrift des Österreichischen Ingenieur- und Architecten-Vereines*.[16] Neumann criticised the over-simplified assumptions underlying Koenen's algorithms for calculating the strength of reinforced concrete members and formulated more realistic substitutes.[17] Moreover, he posited a set of uncertainties which in effect set out the objectives of a research program aimed at improving the calculability of the strength of reinforced concrete structures in the design stage. In order to allow for proper calculations, the value of the elasticity coefficient of concrete was identified by Neumann as a key issue. Since little was known on the properties of concrete, systematic (laboratory) research was deemed necessary (Disco, 1990). By determining what the problems were, Neumann set a direction for a theoretical-experimental project aimed to enhance the theoretical grasp of reinforced concrete.

In 1893, the French weekly journal *La Construction Moderne*, began a series of detailed articles on concrete engineering that appeared for almost a year (Elliot, 1992). In France, Edmond Coignet and Napoléon de Tédesco in 1894 presented a paper to the *Société des Ingénieurs Civils de France* in which they proposed a new method of calculation (Tédesco, 1906). Shortly thereafter, Paul Christophe, a Belgian engineer who had worked as a consulting engineer for *Maison Hennebique*, wrote a series of articles on the pros and cons of reinforced

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[15] *Centralblatt der Bauverwaltung,* nr. 15 of 1886.

[16] *Wochenschrift des Österreichischen Ingenieur- und Architecten-Vereines,* nr. 2, 1890. The fact that reactions could be published in another journal indicates that Koenen's publication was circulating widely throughout Europe.

[17] In a horizontal beam the top half will experience compressive forces, while the bottom half will experience tensile stresses. In a homogeneous beam the "neutral plane" will be exactly in the middle. Koenen had used this ideal model of a homogeneous beam for a reinforced concrete beam. In his calculations, he let the iron rods, located near the bottom of the beam, absorb all the tensile stresses and the concrete in the top half of the beam as the element absorbing all the compressive stresses. Neumann pointed out that concrete in the bottom half would also absorb some of the tensile stresses. Koenen had also ignored the matter of elasticity, which was also criticised by Neumann. When, as in an reinforced concrete beam, top and bottom are composed of heterogeneous materials with extremely different coefficients of elasticity, it cannot be assumed, as Koenen did, that the neutral plane would lie in the middle of the beam. This asymmetry has consequences for calculating the optimal placement and dimensioning of the iron reinforcement as well as the overall dimensions of the beam. Although relatively much was known about the elastic properties of iron by 1890, very little was known of concrete on this point. This lack of concrete parameters prevented Neumann from developing practically useful algorithms, although he was aware that actual Monier beams and plates were considerably stronger than his calculations predicted. This led him to suggest — it later turned out correctly — that the coefficient of elasticity of concrete might be different for compressive, than for tensile stresses and even that concrete might be a non-Hookeian material, i.e. one whose coefficient of elasticity varied with the magnitude of the force applied per cm^2 and hence violated Hooke's law which predicts a linear relationship between tension and deformation (Disco, 1990: 280).

concrete which were published in the Belgian journal *Annales des Travaux publics de Belgique* and the French journal *Annales des Ponts et Chaussees*. Whereas publications of the firms that owned patents of specific systems usually showed finished structures without revealing details that were the firm's stock-in-trade, Christophe's articles withheld little (Elliot, 1992). He showed detailed drawings of reinforcement placements and provided precise descriptions of a large number of projects. Christophe's ideas became widely known and influential, especially after other journals noted and summarised Christophe's articles. The Dutch *Bouwkundig Weekblad*, for example, published Christophe's final instalment.[18] Christophe's series of articles was republished as a handbook *Le béton armé et ses applications* in 1902.

Christophe defended the rudimentary elastic theory that had been developed by Coignet and Tédesco. He argued that a more sophisticated theory would only add complexity, while it would not contribute to make constructions more reliable, due to the many disturbing influences at play on the building site. Larger constructions had to be made on-site, if only because of the limited transportation possibilities of the time. Therefore, the circumstances in which reinforced concrete was applied varied considerably due to variable weather conditions, different levels of supervision, etc.

The content of Neumann's and Christophe's publications indicate that a cosmopolitan approach began to take shape in which reinforced concrete as such was studied and modelled. Also the uptake of reinforced concrete in curricula at polytechnics and universities marked the emergence of a local-cosmopolitan division of labour. In 1897 Charles Rabut, professor of the *École Nationale des Ponts et Chaussées*, gave the first course in reinforced concrete (Lemoine, 1991). After 1900, other polytechnics and technical universities in other countries followed, and theoretical work on reinforced concrete technology increased. Gradually, a new generation of engineers was trained which were taught how to design and calculate reinforced concrete structures.

This increased circulation and aggregation activities occurred in a context which was characterised by attempts to create a common cognitive and legal framework which could reduce financial as well as technological risks. Without adequate institutional arrangements, such a common frame of reference was difficult to achieve. In several countries, governments took the initiative towards standardisation and set up committees, which included civil engineers working for governmental agencies or other professional customers as well as reinforced-concrete contractors with long-established businesses (and vested interests). That the latter participated indicates that it no longer was feasible to follow a strategy of secrecy. As a cosmopolitan level started to emerge, it became important to participate on this level in order to be able to protect their

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[18] Translation: Construction Weekly. It was a weekly journal published by the *Bond van Nederlandse Architecten* (translation: Association of Dutch Architects).

interests, to influence the standardisation process, and to reinforce a good reputation. The customers and inspectorates needed contractors, because they were the actors with relevant expertise and experience. Around 1900, technical literature on reinforced concrete was still relatively scarce and was not very helpful because opinions put forward in the literature often diverged and reflected adherence to proprietary systems. Contractors' secrecy and idiosyncrasies made it difficult for those not working in contracting firms to become knowledgeable. As an effective way to counterbalance contractors' bias towards their own systems, standards had to be based upon theory and systematic experiments. In other words, knowledge had to be made sufficiently robust and general to transcend specifics and idiosyncrasies. The huge variation in systems and application circumstances, made it uncertain whether it would be feasible to create standards that could bring all systems under one common denominator. Opponents to standardisation, in particular incumbent contractors who feared new competition as a result of public availability of a common knowledge reservoir, argued that there were too many factors at play to take everything "*Schablonmässig*" — i.e. to make templates that would fit any situations (Sanders, 1902). If standards for calculation would be given, this might create a false sense of security for inexperienced contractors as well as customers.

In France, an official State committee tried to establish standardised rules for calculation between 1892 and 1900 — which proved difficult given the variety of systems and calculation methods.[19] It proved impossible to aggregate the various test results which had been done by contractors because of the high variability. Reputed engineers trained at the *École National des Ponts et Chaussés*, such as Stellet, Lefort, and Rabut, attempted to coordinate the results of numerous tests carried out by contractors such as Hennebique and Coignet. They tried to deduce from these experiments mechanical laws that would permit a reliable calculation of the elements of a given construction. This proved next to impossible because the mechanical properties of concrete were variable with the quality of sand or gravel, the cement that was used, the degree of fluidity of the mixture, the climatic influences during the hardening process, the age, and with many other surrounding conditions. Only if these variabilities would be reduced in a laboratory setting, meaningful inferences could be made. Specimens would all have to be manufactured under the same conditions (and by the same hands). It could then be researched systematically what the effects of deformation would be for every kind of stress. With such experimental knowledge it would become possible "to navigate in the theoretical domain, and to determine the practical coefficients in such a manner that the formula obtained, would give, as a rule, the dimensions indicated by numerous experiments made on a

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[19] Members of the committee included the Inspector of Water Management Lorieux, and chief engineers Considère, Résal, Rabut and Mesnager.

practical scale." (Tédesco, 1906). As long as reinforced concrete was made on location, variability was inevitable.

Thus, systematic experiments under controlled circumstance were required to establish the properties of reinforced concrete. Such research (which would create a collective good) depended on adequate facilities and funding. In 1900, the French Minister of Public Works established a new committee to make proposals for regulations.[20] The Inspector of General Public Works in Paris, Armand Considère, became manager of the works of the *Commission Ministerielle du Ciment Armé* and did many experiments for the committee (Tédesco, 1906). His experimental work provided the much-needed experimental data. Considère was among the first to perform systematic tests under controlled circumstances with uniform specimens to establish relevant coefficients and formulas. He published a handbook on reinforced concrete, and thus made a substantial contribution to the international theoretical-experimental project.

In 1906 the *Commission* had progressed far enough to establish standards. These standards marked an official acceptance of reinforced concrete as a reliable and "universal" construction technology in France (Lemoine, 1991).[21] The French regulations were liberal and had a provisional character, "in order to leave the door open to the future advances of science." (Tédesco, 1906: 166). The tricky question of whether or not concrete took tensile stresses was resolved pragmatically by allowing the contribution of concrete to be entirely neglected in the calculations.[22] Thus, in absence of a credible technical model, calculations were deliberately simplified. The standards were a compromise and were not supposed to stifle or hinder the practices of reputed, incumbent reinforced-concrete contractors. Constructors were allowed to propose their own calculation methods, provided these could be justified convincingly. Rather than a troublesome building code, the regulations were intended to provide guidance for rational designs, in particular for those who were less experienced and skilful. The pragmatic standards reflected the composition of the committee in which not only "men of science" but also "men of practice" had seated (Lemoine, 1991).[23] Other parties were also engaged in standardisation efforts.

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[20] Members of the committee included the Inspector of Water Management Lorieux, chief engineers Considère, Résal, Rabut, Mesnager, Harel de la Noë, and Bechmann, Colonel Hartmann, Captain of Military Engineering Boitel, architects Hermant and Gautier, and 'cement technicians' Candlot, Coignet and Hennebique.

[21] "Le règlement de 1906 marque l'avénement officiel du béton armé et sa reconnaissance comme une technique de construction sûre et d'application universelle. Après trente ans de tâtonnements [groping around], tout est allé très vite, et peu d'années ont suffit pour mettre au point une doctrine sûre et reconnue." (Lemoine, 1991, p. 274.)

[22] "[A]s it is possible to apply the general laws governing homogeneous bodies; it suffices to take no account of the concrete in tension, and to replace the volume of the principle armatures by a volume of concrete fifteen times greater." (N. de Tédesco, 1906, p. 166.)

[23] "Ce n'est qu'en 1930 que le Règlement publié par la Chambre Syndicale des Constructeurs en ciment armé de France lui apporta des compléments, tenant compte surtout des progrés constatés dans la qualité

The French Army Corps, for instance, also developed regulations for internal use. In 1903 the *Génie Militaire* published a circular in which a calculation method was imposed.

In Germany, the professional engineering society *Verband Deutscher Architecten- und Ingenieur-Vereine* and the newly established *Beton-Verein* took the initiative to draw up provisional standards that were to be included in a handbook with rules on design, construction, and testing of reinforced concrete constructions. In 1901, the *Beton-Verein* set up an *"Erweiterte Beton-Kommission"* (Extended Concrete Committee) to examine reinforced concrete and draw up rules. A key figure in this Committee was Emil Mörsch, the technical director of Wayss & Co., and a "great theoretician of reinforced concrete" (Lemoine, 1991: 275). In 1902 he published the handbook *Der Eisenbeton: seine Theorie und Anwendung*.[24] It became a standard textbook for many years, and was translated in many countries (Elliot, 1992). It contributed to no small extent to the application of the elastic theory of structures to reinforced concrete in a scientific way. The theory, formulated by Mörsch, was later verified by detailed experimental testing at the laboratory of prof. Bach at the Technical University of Stuttgart.[25]

In fact, testing stations played an inconspicuous but vital role in the production of translocal knowledge since properties of reinforced concrete required systematic experiments under controlled circumstances. Testing was very important to establish the performance and to provide experimental data to back-up theories and to determine coefficients and parameters. Test stations were also consulted when a difference of opinion occurred. For most contractors, customers and inspectorates, systematic testing programmes were too expensive to do on an individual basis. Moreover, the objectivity of test results could be questioned by other parties. Test stations could play the role of a trusted third party. As collective goods, test stations had been established in several countries. Besides the renowned test station at the Technical University of Stuttgart, there were test stations in Zürich, Vienna and Prague which were also associated with polytechnic schools. In Belgium and France there were test stations which were administered by railway directorates, and in England a private test station existed near London. In the Netherlands, the building sector and engineering societies had lobbied unsuccessfully for such a test station in

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des ciments et l'amélioration de la résistance des bétons. Le nouveau réglement officiel de 1934, également très libéral, n'ajoutait en fait pas grand chose au réglement de 1906." Translation: "It was not until 1930 that the Regulations published by the Association of reinforced concrete constructors in France were supplemented, taking into account primarily the observed progress in the quality of cements and improvements of the resistance of concrete. The new official regulations of 1934, equally liberal, did not add much to the regulations of 1906." (Lemoine, 1991: 275.)

[24] Translation: Ferroconcrete construction: its theory and application.

[25] These tests established the need for deformed bars for good bonding with concrete and demonstrated that the amount of steel in any member should be limited to about 8% of the area. This would ensure the slow elastic failure of the steel, as opposed to the abrupt brittle failure of the concrete, in case of accidental overloading.

the nineteenth century (Van Leeuwen, 1993).[26] As a Dutch state-funded test station did not become a reality, a private test station was started in 1890 by Koning & Bienfait. In a conference for test stations in Dresden in 1889, regulations for test stations had been established which made test results comparable.

Mörsch's work generated much experimental data from in-depth studies between 1901 and 1906. This work resulted in 1907 in the publication of the regulations of the German committee for reinforced concrete (Lemoine, 1991). In 1904, the Prussian government had already used preliminary results in its official regulations. After a two-year examination of projects by building authorities, the regulations were updated (Elliot, 1992). Whereas the French regulations had been a pragmatic compromise between "science" and "practice", the Prussian regulations prescribed only one method of calculation and were much less liberal. In 1907 the *"Ausschuß für Eisenbeton"* (Committee for Reinforced Concrete) was established which took over most regulatory tasks of the *Beton-Verein's* Committee.

In the same year, the *Internationaler Verband für Materialprüfungen der Technik*, an international organisation for the testing of materials, decided to establish an international Committee for concrete-iron to create an overview of the scientific experiments that had been done in different European countries.[27] Potentially, taken together, various test results could be used to deduce rules for general application — i.e. produce translocal knowledge. The Committee set out to find answers to questions about behaviour of reinforced concrete under tensile and/or compressive stresses. It aimed to promote the unification of (static) calculations, building regulations, as well as delivery conditions (Rutgers, 1907; 1908). It also standardised algebraic expressions and formulas. The Committee did a survey of the tests in different countries; it gathered findings of these tests; it listed contradictions vis-à-vis other empirical results and gave presumable causes of these contradictions; and it surveyed testing methods that appeared to be recommendable to get clear and comparable outcomes. The Committee also gathered information of accidents and collapsed in an attempt to draw lessons from them. These activities contributed to further cosmopolitanisation of reinforced concrete.

The German *Beton-Verein*, established in 1898, was the first technical society for the reinforced concrete sector, and was followed by similar associations in France, Austria, Great Britain and other countries. In Great Britain, were the

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[26] It had been argued that such a test station could formulate objective requirements for materials. Contractors would then be better guarded against unreasonable demands by inspectorates. In addition, domestic producers of new materials could prove that their products were not inferior to established or foreign products (Van Leeuwen, 1993).

[27] This committee had eighteen members, which included authorities on reinforced concrete such as prof. Schüle (chair), prof. Mélan, prof. Mesnager, prof. Rabut, prof. Von Emperger, Sachs, Maillart, and Rutgers.

introduction of reinforced concrete was slower than in France or Germany, the Concrete Institute was established in 1908. It had been a result of a Reinforced Concrete Committee which had been established by the Royal Institute of British Architects (RIBA) in 1906 to inquire into the proper conditions for the use of reinforced concrete in buildings and other structures. As a result of this activity, one of the system owners proposed that other similar constructors should form a trade association. Eventually, a technical society was established to promote reinforced concrete technology as such, rather than a trade association to promote patented proprietary systems. Membership was open to all those professionally or otherwise engaged in the field of concrete.[28] The main objects of the Concrete Institute were "(a) the advancement of the knowledge of concrete and reinforced concrete and to direct attention to the uses to which these materials can be best-applied; (b) to afford the means of communication between persons engaged in the design, supervision and execution of works in which concrete and reinforced concrete are employed; and (c) to arrange periodical meetings for the purpose of discussing practical and scientific subjects bearing upon the application of concrete or reinforced concrete and the production of their constituents." (Hamilton, no date).

In general, the establishment of technical societies was part of the dynamics in which a local-cosmopolitan division of labour emerged and institutionalised, supported by a new, differentiated infrastructure. It indicates that the field became less fluid. The battle of systems diminished, as the various systems were treated as (more or less sound) variants of one new building technology. Once technical societies like the *Beton-Verein* were in place, they provided a mechanism for collective action, in particular collectively funded research and standardisation. They published handbooks, organised meetings, lectures, conferences, etc. Eventually, they began to organise courses and introduced exams that certified skills. They became carriers of professionalisation of the trade, and cosmopolitanisation of the technology. In addition, the establishment of technical societies with their journals, handbooks and conferences further facilitated the (international) exchange of knowledge between the members of these communities.

While standardisation activities increased during the first years of the twentieth century, publications on reinforced concrete technology became more frequent. Professional engineers working for (potential) customers or inspectorates, became increasingly interested in the new technology and some began to involve themselves in discussions and theoretical-experimental activities. As a result, the mysteriousness of reinforced concrete for those not initiated was reduced. As professionals, they could not allow a technology to be applied in

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[28] The Concrete Institute was renamed the Institution of Structural Engineers in 1922 (Hamilton, no date).

(complex) constructions if it could not be calculated reliably. Not before long, the first specialised journals started to emerge. The first specialised journal was *Neuere Bauweisen und Bauwerke aus Beton und Eisen* in Germany in 1901. It was established by Fritz von Emperger who was soon to become a recognised authority on reinforced concrete.[29] In 1905, the journal was transformed into an international specialised journal *Beton und Eisen: Internationales Organ für Armierten Beton*. It was published, not by a professional society or a reinforced concrete company, but by a commercial publisher, Ernst in Berlin.[30] Apparently, in the early 1900s the number of readers and authors was sufficiently substantial to justify this new element in the infrastructure. The same publisher also began to publish the annual *Beton-Kalender: Taschenbuch für Beton- und Stahlbetonbau sowie die verwandten Fächer* in 1905.[31]

Beton und Eisen became an influential journal in the international field of reinforced concrete. Other journals that were established before the First World War included the *Deutsche Bauzeitung: Mitteilungen über Zement, Beton und Eisenbetonbau* and the *Armierter Beton: Monatsschrift für Theorie und Praxis des Gesamten Betonbaues (*both in Germany); the *Revue de la construction moderne en béton et béton-armé* and *Il cemento* (both in Switzerland); *Le fer-béton (système Matrai)* (in France); the *Concrete and constructional engineering* and the *Ferro-concrete* (both in England); the *Concrete*, the *Cement and engineering news*, the *Cement*, and *The Cement Era* (all four in the United States); and, finally, *El cemento armado* and *El hormigon armado* (both in Spain) (Boon, 1913). Within a few years *Gewapend beton* (in the Netherlands) and *Revue du béton armé* (in Belgium) could be added to this growing list.

In specialised journals, works that were made according to different systems, were described and illustrated, reviews of the position of reinforced concrete vis-à-vis traditional construction techniques were given, and developments in theory and practice were noted. Journals gave surveys of technical literatures, book reviews, patents, etc. and provided a forum for debate and exchanges of opinions. The journals helped to map and classify the variety of proprietary systems that were on offer. The variety of systems was recognised for what it consisted in. This allowed for work towards integration, detailed comparisons, and standardisation.

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[29] Von Emperger had studied at the Technology Universities in Vienna and Prague, and had become a consulting engineer in New York in the early 1890s. In 1894, he founded Concrete Steel Engineering Company in New York City. He had given a lecture to the American Society of Civil Engineers on *The development and recent improvement of concrete steel high way bridges* in which he explained the advantages of reinforced concrete technology. In 1897 he returned to Vienna. In 1903 he received a doctorate at the Technical University of Vienna. In 1932 he got a honorary doctorate from the Technical University of Dresden (International Database and Gallery of Structures at www.structurae.de).

[30] The publisher Ernst & Sohn had been established in 1851 (and still exists). It was specialised in architecture and civil engineering and published for the building trade. From 1900, the publisher increasingly specialised in the field of structural engineering. *Beton und Eisen* and the *Beton-Kalender* were among its most important publications.

[31] Translation: Concrete yearbook: paperback for concrete and ferroconcrete construction as well as related trades.

Handbooks became more numerous and more substantial. In English-speaking countries, the most prominent handbook was Charles F. Marsh's *Reinforced Concrete* from 1904. It compared and evaluated the different systems then in common use. This book was later reworked by William Dunn. It is still known as simply "Marsh & Dunn", which indicates its widespread and prolonged use in education as well as practice. Perhaps the most impressive handbook was the monumental fourteen-volume *Handbuch für Eisenbetonbau* (1907) edited by Fritz von Emperger. In this handbook, an overview was given of reinforced concrete technology as it existed at the time. The various proprietary systems were classified into two groups: the 'proper' and the 'improper' reinforced concrete systems. The systems in which iron performed the most important (static) role, e.g. systems by Harel de Noë, Rabut, Matrai, Möller, and Coignet were not considered proper reinforced concrete systems. Proper systems were systems in which iron took (most of) the tensile stresses and concrete the compressive stresses. These included the systems by Monier, Wayss, Hennebique, and Ransome.

With regard to the important matter of calculation, Von Emperger's handbook lined up different approaches. In Figure 4.1, for example, nine methods to calculate the distribution of forces in the cross-section of a loaded beam are shown. The figures present the stresses in a beam loaded with a certain weight. Above the neutral axis the maximum compressive stresses are indicated, and below this axis the tensile stresses that concrete can take. For reasons of safety and economy it was an important question how much tensile stresses concrete was considered to be able to take. For safety reasons it was best to neglect them, and let iron take all these stresses — as in the last three diagrams. For reasons of economy, it was better to assume that concrete took some of the tensile stresses, so that less reinforcement was needed — as in the first six diagrams. Another question was whether the distribution of stresses was linear or non-linear. Theoretically, it was established that it should be non-linear, but from a practical point of view, calculations had to be simple, and therefore a linear distribution was assumed. (Sanders' diagram shows this nicely: the dotted line indicates the approximation that should be used in practice).

The issue with regard to whether or not (and if so, how) concrete would take tensile stresses in calculations, would remain controversial for many years. Pragmatics, like Paul Christophe, argued that it was more important to ensure certain limits were not exceeded, than to establish the correct tensile and compressive forces in the material. Several viable options were recognised when it came to the question whether or not to assume that concrete took part of the tensile stresses.[32] Each of these routes could lead to reliable outcomes as long as the values of the constants and admissible forces were determined by experi-

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[32] The Dutch professor S.G. Everts (1910), for instance, pragmatically recognised three viable ways of calculation.

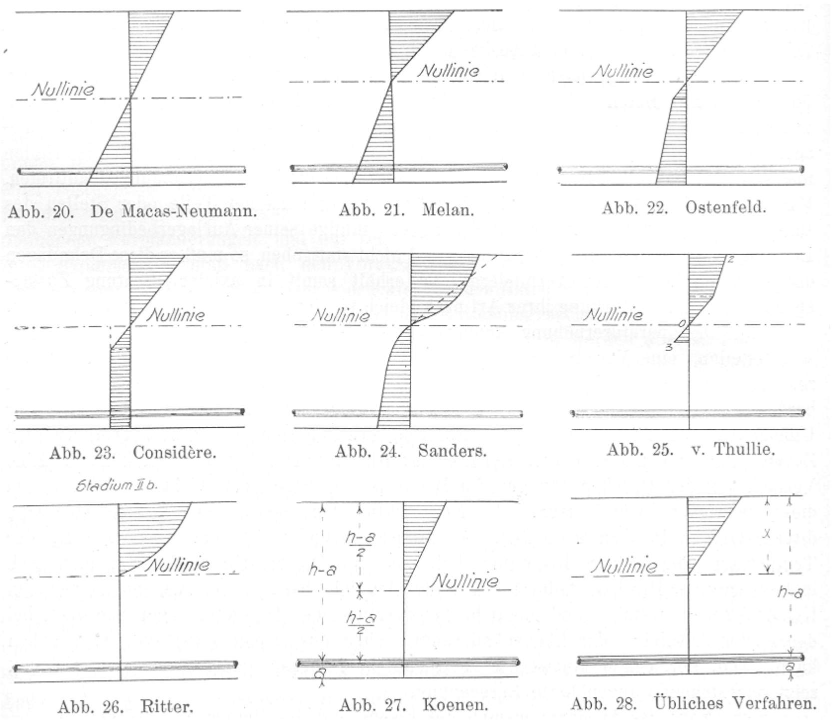
Abb. 20. De Macas-Neumann. Abb. 21. Melan. Abb. 22. Ostenfeld.

Abb. 23. Considère. Abb. 24. Sanders. Abb. 25. v. Thullie.

Abb. 26. Ritter. Abb. 27. Koenen. Abb. 28. Übliches Verfahren.

Figure 4.1. The responses of concrete to compressive stress (top) and tensile stress (bottom) (Von Emperger and Förster, 1912).

mentation. As long as the behaviour of reinforced concrete was not completely understood — i.e. as long a no robust technical model was created — pragmatics argued that theoretical considerations should not be given too high a value. For the time being, experimentation and practical, good "constructional sense" were considered more important that theoretical sophistication (Everts, 1910).

Thus, by 1910, cosmopolitanisation processes had been set in motion, and reinforced concrete was no longer a deeply mysterious, local, heterogeneous set of local solutions to specific problems. A local-cosmopolitan division had emerged, supported by existing as well as new infrastructures. Technological knowledge was partly institutionalised in standards. At the same time, experiential know-how remained important to create reliable structures — if only to interpret the building regulations adequately.

A major affordance for cosmopolitanisation was the involvement of demanding, professional customers who would not trust the new technology unless it was theoretically underpinned. The presence of engineering societies further stimulated cosmopolitanisation. Once established, engineering societies like the German *Beton-Verein* came to play an important role in the production and dissemination of knowledge.

4.3 Cosmopolitanisation in the Netherlands

4.3.1 Situation before 1890s

Before the 1890s, reinforced concrete was scarcely known in the Netherlands. This relative backwardness in comparison to countries like France, Belgium, Germany and Austria, was partly the result of the Netherlands' late industrialisation (Disco, 1990). Also the limited size of the Dutch construction market probably played a role (Schippers, 1995).[33] Because the Dutch professional engineering community was internationally oriented, some news about the new technology was published in Dutch engineering journals in the second half of the 1880s. The two Dutch engineering journals at the time were the *Tijdschrift van het Koninklijk Instituut van Ingenieurs*[34] and *De Ingenieur*,[35] published by the professional societies *Koninklijk Instituut van Ingenieurs* (KIvI)[36] and the *Vereeniging van Burgelijke Ingenieurs* (VBI)[37] respectively. One of the few pieces in *De Ingenieur* on reinforced concrete was a review of Koenen's article in the *Zentralblatt für Bauverwaltung* of 1886 about a new floor construction using "recently invented (sic) cement slabs (system Monier) which consists of interwoven iron wire or interwoven thin iron rods, covered on both sides with a layer of firmly stamped cement mortar." (*De Ingenieur*, 15 May 1886, quoted in Disco, 1990).[38] The fact that the reviewer found it necessary to describe, rather than merely note, the Monier system, indicates that it had not yet become a household word in engineering circles in the Netherlands (Disco, 1990). In 1890, the *Tijdschrift van het KIvI* reported on Paul Neumann's theoretical exposé which had been published in the *Wochenschrift des Österreichische Ingenieurs- und Architecten-Vereins* (*Tijdschrift van het KIvI*, 1890-91: 164). In general, the two main Dutch engineering journals kept their readers informed of international developments by providing weekly reviews of the foreign technical press (Disco, 1990). Since Dutch engineers were competent readers of German, French, and English, they could be conversant with foreign literature (Disco, 1990).[39]

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[33] Schippers (1995) mentions that there was no domestic cement industry. While traditional construction materials, like bricks, were widely available, cement had to be imported from foreign (Portland) cement producers. Another inhibiting factor was that the Dutch soft soil was not well-suited for arched bridges.

[34] Translation: The Journal of the Dutch Royal Institute of Engineers. It was published between 1870 and 1916, when it merged with *De Ingenieur*.

[35] Translation: The Engineer.

[36] Translation: Royal Dutch Institute of Engineers.

[37] Translation: Association of Civil Engineers.

[38] *De Ingenieur* also reported in 1890 on Wayss & Co's spectacular footbridge at the Industrial Exposition in Bremen (*De Ingenieur*, 1890, nr. 42, 395).

[39] Two foreign journals that particularly active in reporting on reinforced concrete, the German *Zentralblatt für Bauverwaltung* and the Austrian *Wochenschrift des Österreichische Ingenieur- und Architectenvereins*, were available in the library of the KIvI (Disco, 1990).

Until the 1880s there was no knowledge production on reinforced concrete in the Netherlands. In the 1890s, this would change as contractors took up reinforced concrete and potential customers began to be interested in the new building and construction technology. In the twentieth century, Dutch contractors and engineers would become important knowledge producers themselves, and would become part of an (international) local-cosmopolitan division of labour.

The first reinforced concrete contractor in the Netherlands was a branch office of a Belgian firm, *Gebr. Fr. & J. Picha*. This Belgian firm had bought Monier's patent soon after the World Exhibition in Antwerp of 1879 in which reinforced concrete had been displayed. This exhibition was probably among the first exhibitions that attracted some attention for reinforced concrete in the Netherlands. In 1888, *Gebr. Fr. & J. Picha* set up a branch office, named *Picha-Stevens*, just across the border in the Dutch town Sas van Gent. The company used the Monier system to produce relatively simple constructions such as water reservoirs, sewer pipes, waterproof cellars, small tunnels, and floors. In an effort to promote the new technology, *Picha-Stevens* sent in a rain water reservoir and a rowing boat to the *Zeeuwse Nijverheidstentoonstelling* of 1888 organised in the Dutch city of Middelburg. The water reservoir was awarded a prize, and in the newspapers enthusiastic mention was made of the new 'miracle material'. Its waterproof and fire-resistant qualities were commended, and new ways of construction and building were envisioned. The *Nieuwe Rotterdamsche Courant*, for example, reported that if this system would prove satisfactory in practice—which at that time was not certain—then wood and all flammable materials can be avoided in making public buildings (NRC, 3 July 1889). *Picha-Stevens'* success at this regional industrial exhibition and its positive reviews in the newspapers, drew the attention of a company that was specialised in making wood durable, the *Maatschappij tot houtbereiding tegen bederf, Afdeling Cement*.[40] In 1890, it started, together with *Picha-Stevens*, a new company called the *Amsterdamsche Fabriek van Cement-IJzerwerken (systeem Monier)*.[41] This company was to become influential in the Netherlands during the 1890s and 1900s. During the 1890s, few other companies, including the *Rotterdamsche Cementsteenfabriek Van Waning & Co*, took up cement-iron works in their line of work and started with the production of simple "Monier works" like floor slabs, waterproof cellars, pipes, culverts, tanks, etc. Not until after 1900 new specialised contractors would enter the market.

In the Netherlands, the actor-constellation was characterised by the presence of a large professional potential customer for reinforced concrete constructions, namely the national Public Works Administration *Rijkswaterstaat* which was responsible for improving and maintaining dikes, rivers, canals, locks,

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[40] Translation: Company for wood preparation against decay, Department Cement

[41] Translation: Amsterdam factory of cement-iron works (system Monier).

roads, bridges, and other infrastructural works that were under control of the national state. *Rijkswaterstaat* initiated and detailed public works projects, drew up specifications, invited and judged tenders, and supervised their actual execution by private contractors. Because *Rijkswaterstaat* was by far the largest employer for civil and hydraulic engineers, its engineers played a hegemonic role in the professional society KIvI. *Rijkswaterstaat* not only was in a position block or build a public sector market for reinforced concrete contractors — by formulating specifications either for or against reinforced concrete — , but it was also in a position to make the new technology acceptable, by defining it as scientific, responsible, and trustworthy (Disco, 1990). Thus, *Rijkswaterstaat* was a crucially important customer for reinforced concrete contractors.

In 1893, *Rijkswaterstaat* made its first work in reinforced concrete. It had been granted to Wayss & Co. rather than the recently established domestic *Amsterdamsche Fabriek*. A *Rijkswaterstaat* engineer, Tutein Nolthenius, became enthusiastic about reinforced concrete, and reported on his experiences in a lecture in a meeting of KIvI. His enthusiasm was not widely shared. KIvI engineers questioned the calculability and durability of reinforced concrete constructions. *Rijkswaterstaat* gave him a two-year leave to do tests on Monier slabs, the results of which he presented in 1895. He concluded that although there were differences between the tentative theoretical model (which had been developed by foreign experts) and practice, reinforced concrete could be applied if sufficient safety margins were taken into account.

Studies of reinforced concrete were not only made within *Rijkswaterstaat*, but also within military circles. Captain W.J.M.van de Wijnpersse, for instance, studied the new technology extensively. In the 1890s he published his findings in *De Ingenieur*. In 1902, he would published a handbook of civil engineering in which reinforced constructions were discussed next to traditional building materials as iron, wood and stone (Van de Wijnpersse, 1902).

At the end of the 1890s, the claimed advantages of reinforced concrete such as economy, waterproofness, fire resistance, shockproofness, did not fail to impress customers.[42] But the enigmatic nature of the technology also caused scepticisms and reservations. Reinforced concrete constructors that wanted to

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[42] While reinforced concrete technology was met with wary interest by civil engineers, architects showed little interest and had greater reservations. As long as the new material was limited to waterproof cellars, structural elements like stairs, and fireproof floors in (public) buildings, they had no objections. But when it came to using the new technology to make complete buildings (as had been done in France and elsewhere) they opposed it. For one, as artists rather than engineers, they were concerned with the aesthetics of reinforced concrete constructions. The new material tampered with age-old traditional and aesthetical ideas. In addition, the introduction of reinforced concrete was seen as another attempt of civil engineers to make inroads in their domain. Architects viewed reinforced concrete like they had viewed iron and steel in the nineteenth century: as an engineers' material, suited for constructions like bridges and commercial and industrial buildings, but not for buildings. In addition, most architects could not made the complex calculations that were required for iron and/or reinforced concrete constructions. Not until after the First World War, modernist architects would discard traditional, decorative styles and seek to merge architecture with industry. They would develop a simple, logical, functional building style in which reinforced concrete would play an important role.

tap into the market controlled by bureaucratic state agencies and other large professional customers, such as railroad companies, had to develop technological knowledge which was reliable and replicable. These customers demanded clear links between designs on paper and eventual performances, and they wanted to be able to judge designs according to standardised criteria. In particular, they preferred mathematical algorithms which could demonstrably be derived from well-founded assumptions and experimentally established parameters (Disco, 1990).

Thus, ambitious reinforced concrete contractors that wanted to penetrate the market of professional customers had to convince professional engineers of the reliability and the soundness of their designs and calculations. In surrounding countries, contractors like Wayss & Co. and Hennebique had already ventured into theory. *Rijkswaterstaat* engineers, if at all prepared to put their professional reputation on the line for a technology that lacked a sound theoretical basis, put more confidence in reputed foreign contractors than small domestic contractors like the *Amsterdamsche Fabriek*.[43] In order to increase competitiveness, domestic contractors began to venture in theory themselves — i.e. become active on the emergent cosmopolitan level. The most ambitious contractor was the *Amsterdamsche Fabriek* under the capable leadership of its director L.A. Sanders. Sanders tried to develop a theory based on experiments with the Monier system. In 1898-99 he published his findings in a series of articles in *De Ingenieur* entitled *Onderzoek naar de theorie der beton en cementijzer-constructiën* (Sanders, 1898-99).[44]

4.3.2 Knowledge production and standardisation in the Netherlands

Besides *Rijkswaterstaat* and the military engineering corps, also some public works departments in large cities became interested in reinforced concrete at the end of the 1890s. An example of how potential customers helped to introduce reinforced concrete technology in the Netherlands, is the lecture by an engineer of the Rotterdam Public Works department Wouter Cool in 1900 (Cool, 1900). He had travelled to France to study the possibilities of using reinforced concrete for the extension of the Rotterdam gas plant. While in France, he had visited the World Exhibition in Paris in 1900 where several reinforced

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[43] Sanders (1901a) of the *Amsterdamsche Fabriek* complained that this had more to do with advertisement campaigns by foreign contractors such as Hennebique, than with expertise. "With some tests, and a bit of good will, the Dutch could had been given the honour to apply this [new technology] themselves for the first time in their own country — where it can become of so much significance. However, it seems that large advertising, is more effective in getting a contract and more rapidly than the most serious studies in the theoretical domain. It is a shame that a Dutchman, for the sake of his fellow Dutchmen, cannot advertise." (Sanders, 1901a: 259).
Translated from: "Met een paar proeven, en wat goeden wil, had men den Hollanders de eer kunnen geven dit in hun land — waar dit van zooveel beteekenis kan worden — voor het eerst zelf toe te passen. Het schijnt echter dat een bij uitstek groote reclame meer tot het doel leidt en zelfs vlugger dan de meest ernstige studies op theoretisch gebied. Jammer dat een Hollander, ter wille van zijne mede-Hollanders, geen reclame mag maken."

[44] Translation: Research on the theory of concrete and cement-iron constructions.

constructions by various contractors, including Hennebique and Coignet, were displayed. During his visit Cool had formed an opinion on the various systems that existed in France, which he presented in a KIvI meeting. In his lecture, Cool based himself on Christophe's series of articles *Le béton-armé et ses applications*. Cool thought it useful to make Dutch engineers familiar with this work which was sold out and hard to come by in the Netherlands. (The series would be republished as a handbook in 1902).[45] Following Christophe, Cool argued that only systems in which designs were based on the complementary roles of iron (taking most of the tensile stresses) and concrete (taking most of the compressive pressures) were proper reinforced concrete systems. Only systems which could not be calculated were to be used by professional engineers. Assurances of contractors were insufficient to create reliability and acceptability. In his lecture (which was published in *De Ingenieur*), Cool addressed the controversial topic of reliability and rusting due to fissures, requirements that concrete and iron had to satisfy, methods of construction, ways of calculation, test results, and theoretical developments. In his efforts to introduce reinforced concrete to the Dutch professional engineering community, Cool based himself solely on foreign knowledge sources, and completely overlooked recent knowledge production, e.g. by Sanders of the *Amsterdamsche Fabriek*. Sanders reacted with an entry in *De Ingenieur* to signal that relevant knowledge was also being produced in the Netherlands (Sanders, 1901b).[46]

The increased interest of customers was reflected in the establishment of new contractors which specialised in reinforced-concrete technology. In 1900 a railway company had asked A.C.C.G. van Hemert, a professional engineer who had authored an influential handbook on applied mechanics and had lectured at the *Koninklijke Militaire Academie*,[47] to visit a congress on the system Hennebique in order to assess the opportunities of using reinforced concrete for a railway viaduct in Rotterdam. His report had been very positive. Only Hennebique's method of calculation was found to be inadequate. As a result, the railway company had started to negotiate with Hennebique, and Van Hemert had been asked to become a consultant. The calculations of *Maison Hennebique* remained a problem, and eventually, the railway company awarded the contract to Van Hemert himself. In 1902 Van Hemert started his own company, the *Hollandsche*

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[45] In 1906 Paul Chistophe's handbook was published in a German translation: *Das Beton und seine Anwendung im Bauwesen.* (Reviewed in *De Ingenieur*, 1906, nr. 11, pp. 202-3).

[46] Sanders (1901b) hoped that it would become clear to Dutch civil engineers, "that they did not always have to go abroad to find out the truth." He considered Cool a francophile with a penchant for Hennebique. Sanders complained that there had been a proliferation of proprietary systems which had added to the confusion and reluctancy that surrounded the new technology. Actually, he claimed, most systems were nothing more than extensions of the original Monier system. The acceptance of the new technology was hindered by entrepreneurs who promoted their own systems and emphasised their uniqueness, rather than the similarities.

[47] Translation: Royal Military Academy.

Maatschappij tot het maken van werken in gewapend beton.[48] The railway viaduct was the first large project in the Netherlands in which reinforced concrete was used and which was executed by a Dutch contractor. In order to increase his competitiveness, and to create and extend a market for reinforced concrete, Van Hemert contributed to the ongoing collective theoretical-experimental project in which reinforced concrete knowledge was made less local and system-specific. Illustrative of his involvement was his contribution to a discussion on the reliability of reinforced concrete — one of the several debates on reinforced concrete that occurred in the early 1900s. In 1902 *De Ingenieur* published a critical piece on reinforced concrete in which the reliability of "concrete-iron constructions" was questioned by the military engineer Hackstroh (Hackstroh, 1902).[49] Van Hemert jumped to the occasion to make it clear that reinforced was indeed a reliable, calculable technology. A prolonged debate developed in consecutive issues of *De Ingenieur* which offers insights in the state of affairs with regard to cosmopolitanisation of technological knowledge. Van Hemert countered by pointing out that Hackstroh's concerns were anything but new, and had already been addressed by reputed foreign engineers like Considère, Rabut, Christophe, Melan, Ritter, Möller, as well as *Rijkswaterstaat* engineers. All these engineers had had positive experiences with the new technology (Van Hemert, 1902).[50] He rhetorically asked whether these expert opinions did not offset sceptical opinions of those who had not had any experiences themselves. Van Hemert referred to many tests that had been performed, and many experiments that had been done (by himself and others), which all indicated that

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[48] Translation: Holland Company for the construction of works in reinforced concrete, Inc. Among the members of the board was S.G. Everts who would later become chairman of the standardisation committee of KIvI as well as professor at the TH Delft.

[49] The military engineer Hackstroh had written his critical article after he had attended a lecture of three *Rijkswaterstaat* engineers who had reported enthusiastically on their experiences with the new technology. Hackstroh, however, had not been convinced about their claims concerning the rustproofness of reinforced concrete, due to fissures. He also questioned the way in which constructions were made. In practice, constructions were never made precisely according to calculations and drawings. Close supervision was necessary to prevent ignorant workmen from positioning the iron incorrectly. Furthermore, a long curing time would reduce the advantage of a quick execution. In addition, restorations and renewals were not possible with reinforced concrete.

[50] Disco (1990) points out that even though Van Hemert referred to almost every reinforced concrete theorist and constructor of any name, he did not mention knowledge production of his rival Sanders of the *Amsterdamsche Fabriek*. Indeed, Van Hemert's piece may be regarded also as a critique of Sanders' methods of calculation. Van Hemert argued why tensile stresses in the concrete should be discounted in calculating the strength of a construction. Sanders, by contrast, had insisted that these stresses should be included. Van Hemert's approach increased the margin of safety considerably, though it naturally gave rise to speculations about fissures in the concrete and implied heavier and more expensive constructions. As the Hackstroh-Van Hemert debate continued, Sanders continued to be totally neglected, although many other foreign experts were called upon in support of various positions. Sanders, for his part, completely ignored the Hackstroh vs. Van Hemert debate in his subsequent publication in *De Ingenieur* (Sanders, 1902). Only in his 1907 handbook, he would give credits to Van Hemert for his contributions to the new technology (Disco, 1990).

reinforced concrete indeed was reliable.[51] Van Hemert admitted to Hackstroh that not all theories that circulated were equally reliable. But if this should mean that "nowadays we still would have to take the empirical way, then we must, after the results of the last years, protest most strongly." (Van Hemert, 1902). Although not all theoretical issues were resolved, and calculations were often laborious and complex, the theoretical achievements should not be given up. Substantial parts of the knowledge base were already made translocal. The fact that not all aspects of reinforced concrete were understood and susceptible for calculation should not be seen as a prohibitive objection. He compared reinforced concrete to the vault which had been built for centuries without proper theory. For a long time the vault had been calculated using an empirical rule which could only establish the possibility of stability. A theoretical-experimental project had resulted in the elastic theory, which initially had met with scepsis, but eventually demonstrated its usefulness convincingly. Van Hemert argued that the same would happen with reinforced concrete. The "irrefutable logic of facts" would slowly but surely make prejudices disappear, and "ways will be opened up that will lead to true knowledge of the material", and therefore also to a reliable calculation of constructions (Van Hemert, 1902). A "scientific" approach to the new technology was seen as the way to create acceptable, reliable and credentialed knowledge. Illustrative of Van Hemert's activities on the cosmopolitan level are his publications in *De Ingenieur* in which he reported on his own works in reinforced concrete and findings from his research. He also held lectures in meetings of KIvI which were subsequently published (Van Hemert, 1904a; 1904b; 1904c). In his lectures he reported on his research on the properties of reinforced concrete, and on advances made in the theoretical-experimental project through the efforts of himself and others, e.g. the standardisation committee of the French Minister of Public Works.

Meanwhile, Van Hemert's rival Sanders continued to make contributions to a collective knowledge reservoir. In 1902, four years after his first series, Sanders (1902) published another series of three long theoretical articles on the calculation and testing of reinforced concrete constructions in *De Ingenieur*.[52] At first, his publications did not incite much reaction among Dutch civil engineers, and Sanders became frustrated by their passive and unresponsive attitudes. When his (translated) articles were published in foreign journals, he found a much more appreciative public for his theoretical ventures. In Germany, Austria, and France he eventually came to be acknowledged as a prominent expert. As a result, he also became recognised as an expert by the Dutch technical establishment. Thus, Sanders not only contributed to the cosmopolitanisation of the

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[51] Hackstroh remained sceptical, and the debate was continued in subsequent issues of *De Ingenieur*. Even in 1904, after a lecture by Van Hemert to KIvI, Hackstroh could not resist to make critical remarks (Van Hemert, 1904c).

[52] Another publication of Sanders in *De Ingenieur* is Sanders (1903).

reinforced-concrete technology, but in the process he also created a reputation for himself and his company.

As reinforced-concrete technology became increasingly applied by customers like *Rijkswaterstaat*, the municipal public works department and rail companies — which were also major employers of professional engineers — , reinforced-concrete technology was taken up in courses at the *Polytechnische School* in Delft. The first lectures on reinforced concrete were given by professor S.G. Everts in 1903.[53] In surrounding countries, reinforced concrete had already been included in technical syllabi at polytechnics and technological universities in the late-1890s. Apparently, there was a demand for engineers who could calculate constructions, and make rational applications, or who could control such calculations and applications. The uptake of reinforced concrete in universities further induced cosmopolitanisation. It called for the development of course materials, i.e. aggregated technological knowledge in the form of formulae, rules of calculation, standards, models, etc. It also resulted in students being trained in the new building and construction technology. In other words, it afforded production as well as distribution of translocal knowledge.

Meanwhile, in surrounding countries, collective efforts to standardise reinforced concrete were well underway (see section 2). In the Netherlands, it was anticipated that such standards would also be required to make reinforced concrete a widely acceptable technology. Such standards could provide a legal framework and create trust between contractors and customers. Especially smaller customers required a framework for they could not judge the soundness of designs of reinforced-concrete constructions themselves. Absence of building regulations which took reinforced concrete into account made it difficult for customers to award contracts to reinforced-concrete contractors. In case something went wrong, there had to be regulations to fall back on. Civil servants working for public works departments, for instance, often refused to apply the new technology because they could not fall back on regulations in case constructions would collapse. For reinforced-concrete contractors, regulations would open up the market for customers that were hesitant to use the new material, and regulations would protect them from idiosyncratic requirements by customers who were not familiar with the material. In general, contractors often felt they were at a disadvantage vis-à-vis customers and their engineers and architects, since they often had to bear all responsibilities of construction. Thus, there was an affordance to contribute to standardisation and thus disclose parts of their knowledge, also because it offered an opportunity to influence the outcomes, and to strengthen their reputation.

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[53] The *Polytechnische School* (1864-1905) was renamed in *Technische Hogeschool* (1905-1986), and eventually in *Technische Universiteit* (1986—). Everts was no stranger to the new technology since he was a member of the Board of Van Hemert's *Hollandsche Maatschappij.*

In 1906, during the first meeting of the newly established section for civil engineering within KIvI, Captain W. Hanegraaff proposed to set up a standardisation committee to establish regulations for reinforced concrete constructions. An important challenge for the committee would be to reduce heterogeneity and end controversies. Hanegraaff argued that "regulations that apply generally" were badly needed because there were diverging notions with regard to the executions as well as calculation of reinforced concrete constructions.[54] A Dutch committee was required because regulations could not simply be modelled after the German (or French) regulations, if only because the standards drawn up by both the German Minister of Public Works and the *Beton-Verein* were conflicting on several points.[55] To be acceptable for professional engineers, standards could not solely be based upon empirical rules. Although KIvI did not have legislative powers, it was emphasised that KIvI should strive for general application of the regulations in the Netherlands. Because most civil engineers working for large customers were members of KIvI, not much problems were expected in this regard. The official request by Hanegraaff was already anticipated by the board of the section, and a budget had already been reserved. Nine members were appointed in the *Beton-ijzer-commissie*:[56] These members were engineers from *Rijkswaterstaat*, public works departments from large cities, the army corps of engineers, a railway company, and two reinforced-concrete contractors, i.e. Van Hemert and Sanders.[57] Thus, in the committee, professional customers together with contractors cooperated in an effort to produce technological knowledge that could be used as a foundation for regulations.

In 1908 the *Beton-ijzer-commissie* finished a draft of the regulations which was published in *De Ingenieur* in 1909 to elicit comments (Tellegen *et al.*, 1909). After the comments were processed, the regulations were presented to KIvI in 1911. After an extensive debate within KIvI, the regulations were adopted vir-

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[54] "In this area we are still very backward due to a lack of regulations that apply generally. There are conflicting notions: the execution and calculation of these constructions is done in the most diverging ways, so that it would be a big step forward if unity could be created." (Minutes of the meeting of 17 March 1906, supplemented to *De Ingenieur*, 1906, nr. 26.)

[55] "The fact that two so competent bodies have such a different opinion, indicates the great difficulties that are connected with the drawing up of such regulations, therefore there is cause to have a committee to study this question thoroughly." (Minutes of the meeting of 17 March 1906, supplemented to *De Ingenieur*, 1906, nr. 26.)

[56] Translation: Concrete-iron committee. Reinforced concrete was referred as "concrete-iron", which was the name that the *Amsterdamsche Fabriek* had used since its foundation. Its rival, the *Hollandsche Maatschappij* used the name "reinforced concrete", after Hennebique's *béton armé.*

[57] The nine member were: J.W.C. Tellegen (chair; director Public Works Arnhem), M.B.N. Bolderman (secretary; *Rijkswaterstaat*), H. van Oordt (*Rijkswaterstaat*), A.W.C. Dwars (Public Works Utrecht; Dwars went abroad in 1907), S.J. Rutgers (Public Works Rotterdam), W. Hanegraaff (Army Corps of engineers), F.C.J. van der Steen van Ommeren (*Staatsspoor*), A.C.C.G. van Hemert (*Hollandsche Maatschappij*), and, finally, L.A. Sanders (*Amsterdamsche Fabriek)* (Disco, 1990: 327).

tually unchanged. One remarkable issue in the discussions had been the name of the technology. The Committee had been forced to drop the name *beton-ijzer* and to adopt the name *gewapend beton* as the official name for the technology. This was more than a purely semantic issue, because *gewapend beton* referred to Hennebique's *béton armé*, while *beton-ijzer* was considered more neutral, and was analogous with the German *Betoneisen*.[58] After *gewapend beton* was adopted as the official name, other names would eventually become obsolete. The technology, which had started out as a heterogeneous collection of systems with different names, had been brought under one common denominator. In 1912, the *Gewapend Beton Voorschriften* (abbreviated as GBV 1912) were published by KIvI. It counted 33 pages, subdivided in three sections (materials, execution, and calculation). In the first section on materials, the relevant materials (cement, sand, gravel, chippings, concrete and iron) were addressed, properties given, and norms established. In the second section on execution it was prescribed that the executor had to be fully knowledgeable about reinforced concrete and that the workers had to be properly trained. In the third section methods of calculation, formulas, variables, standards etc. were presented and explained.

Shortly after the *Beton-ijzer-commissie* had been established, Sanders, who was himself a member of this Committee, had published a comprehensive handbook *Het cement-ijzer in theorie en praktijk* in 1907 (Sanders, 1907).[59] It would soon become a standard work for civil engineers in the Netherlands. In his book Sanders seized the opportunity to set straight the many inaccuracies ("even regarding the history of the trade") that were spread in lectures in the Netherlands. With his book, Sanders wanted to resolve incomprehensions and lack of clarity that surrounded the new technology. Thus, he made a considerable contribution to making available knowledge that had been aggregated over the years by himself and many others. Apparently, it had become counterproductive to keep knowledge local and secret. In the first part he gave an overview (and review) of the many contributions and contributors to the theoretical development of reinforced concrete (or "cement-iron" as Sanders called it).[60] In the second part he focused on tests and standards. Sanders signalled a trend towards standardisation in Europe since 1900. According to Sanders, this trend had been caused by badly executed constructions, collapses, as well as fierce competition coupled with a "hunt for patents". In the final part he gave his

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[58] Actually, Wouter Cool who had initiated the discussion, was known to be a francophile and an adept of Hennebique (Disco, 1990).

[59] Translation: Cement-iron in Theory and Practice. The publisher had wanted to publish an original book in Dutch and Sanders was happy to oblige (Sanders, 1907).

[60] Sanders discusses the work of: M. Koenen, Paul Neumann, Prof. J. Melan, Tutein Nolthenius, Ed. Coignet en N. de Tédesco, Joseph Anton Spitzer, Prof. Max. R. von Thullie, Hauptmann Julius Mandl, Prof. A. Ostenfeld, W. Carling, Dr. Ing. Fritz von Emperger, R. Latowsky, Joh. Hermanek, L.A. Sanders, L. Geuszen, Considère, Paul Cristophe, Prof. E. Mörsch, A.C.C.G. van Hemert.

vision on the history of reinforced concrete — and criticised others who deliberately underplayed Monier's role. Apparently, it was important to have a canonical history of the trade in a period in which the technology was crystallising out. He also described applications of reinforced concrete (especially those executed by the *Amsterdamsche Fabriek*) in different domains.[61] Sanders' comprehensive book (646 pages) was an important landmark in the cosmopolitanisation of reinforced concrete technology in the Netherlands and Europe. His book was put on a par with books by Christophe, Considère, Mörsch and other experts.[62] It indicates that Dutch contractors had reached a level of knowledgeability and expertise that measured up to foreign contractors like Hennebique.

Not before long, more domestic handbooks were published in the Netherlands. The first practical handbook, for instance, was written by another employee of the *Amsterdamsche Fabriek*, namely chief engineer A.A. Boon.[63] It was published in 1908 as *Gewapend beton: Een handleiding voor de studie van materialen, constructie en statische berekening, ten dienste van architecten, bouwkundigen, opzichters, studeerenden, enz.*(Boon, 1908).[64] According to Boon, the application of reinforced concrete had increased to such an extent that no architect, supervisor, etc. could escape the study of this way of building. He claimed to have written his handbook because he had noticed a great lack of knowledge, even among the executors of works in reinforced-concrete. Boon stressed that reinforced concrete was a risky material in the hands of incompetent, unskilled men.[65] Boon attributed the accidents which had happened with "many works in reinforced concrete" to incompetence and recklessness rather than the lack of soundness of the technology itself. In other words, he regarded the technology itself as reliable, while practitioners had to be trained and supervised in order not to undermine this reliability. Thus, he advocated a reversal, in which (cosmopolitan) rules would come to guide (local) practitioners.

In 1909, in the same year as the preliminary regulations for reinforced concrete were published in *De Ingenieur*, S.J. Rutgers, who also was a member of the standardisation committee, became the first lecturer at the *Technische Hoogeschool* Delft. Rutgers had learnt his trade as an engineer of the Rotterdam Public Works department. His cosmopolitan orientation was also demonstrated by his

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[61] The proper order of contributors, according to Sanders, was Monier, Wayss & Koenen, Hennebique, E. Coignet & Tédesco, Matrai, Bordenave, Cottancin, Melan, Ransome. Apparently, in an emerging self-conscious industry, it was important to have a shared history.

[62] In Germany, Sanders was given an honorary doctorate for his accomplishments — an honour seldom received by Dutch engineers.

[63] Later he was to become the first chairman of the *Betonvereniging* (the Dutch association for study of concrete.)

[64] Translation: Reinforced Concrete: A guide for the study of materials, construction, and static calculation, at the service of architects, structural engineers, supervisors, students, etc.

[65] Accidents were not uncommon (S.J. Rutgers, 1908).

membership of the *Internationaler Verband für die Material Prüfungen der Technik*. His speech *De beteekenis van het beton-ijzer als constructie-materiaal*,[66] which was published in *De Ingenieur*, gives indications that reinforced concrete was becoming increasingly popular and that an increasing number of Delft engineers were getting familiar with the new composite building material (Rutgers, 1909). Rutgers announced that in his lectures he would address the properties of the composite material and construction methods. He was well aware that theory was not very sophisticated yet, and stressed the need for practical experience. As a teacher he could only strive for a general picture of difficulties that might emerge, and the ways in which these could be overcome. For students that really wanted to become knowledgeable about reinforced concrete, further study and especially working in practice would be required. Rutgers warned that approximating calculations should not be overvalued, because it would be impossible to develop a calculation that would take into account all factors. Variability on location was too high, and the quality of reinforced concrete was determined to a large extent by the qualities of the constitutive materials. These qualities were not as self-evident or predictable as in the case of iron constructions — if only because concrete had to be made on location in varying circumstances. Moreover, in 1909 many different systems were in use which all had their own methods of construction and calculation. A good "constructional sense" was indispensable in design and construction. Rules could only provide limited guidance, and actual application required local knowledge.[67] In other words, according to Rutgers, because of high variabilities local knowledge remained as important as cosmopolitan knowledge.

The publication of the first *Gewapend Beton Voorschriften* (GBV 1912) was an important milestone in cosmopolitanisation of reinforced concrete (KIvI, 1912). GBV 1912 incorporated credentialed knowledge on reinforced concrete. The Committee had had a strong preference for knowledge that was derived from well-founded assumptions and experimentally established parameters. Article 17, for instance, read "The calculation must be done in accordance with statics and elasticity theory. It may not be executed according to empirical rules." (KIvI, 1912: 14). This was a way to get away from idiosyncratic, local methods to design, construct, or calculate. However, in several instances the Committee had to fall back on empirical rules that were commonly used in practice. Certain rules for calculation could only be based on experiential findings.[68] This empiricism was not the most preferred mode of knowledge produc-

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[66] Translation: The meaning of the concrete-iron as construction material. Rutgers held his speech at 29 September 1909.

[67] Everts (1910) makes a similar point.

[68] The second, updated, edition of the regulations in 1918 read: "The calculation must be in accordance with statics and elasticity theory. It may, except for what is specified in art. 21, not be executed according to empirical rules." (Boon, 1920; translated from Dutch)

tion for professional engineers, who based their status in part on translocal esoteric knowledge. At the time, variety and variabilities inherent in the application of reinforced concrete in practice were too high to let the standards cover everything.

Reinforced concrete contractors had been waiting anxiously for GBV 1912. It was a signal that reinforced concrete had become acceptable and trustworthy. Contractors' eagerness for quick and wide introduction of the regulations is illustrated by the *Koninklijke Rotterdamsche Betonijzer Maatschappij voorheen Van Waning & Co.* which asked KIvI for some hundreds of copies of the official booklets because the company wanted to distribute them freely among architects and other relevant actors.[69] Thus, standardisation of the technology (based on aggregation) helped contractors to convince sceptical customers. It also helped to strengthen the position of reinforced-concrete contractors vis-à-vis their customers. In 1907 a Board of Arbitration had been established which could mediate between contractors and customers in case of conflict. For specialised reinforced-concrete contractors, however, this arbitration was not very attractive, because the arbitration board was not very knowledgeable about reinforced concrete. Therefore, they had wanted the regulations to be as unambiguous as possible. At the same time, they did not want the rules to be made too strict. For example, the length of time that concrete should harden had been part of negotiations within the Committee. While customers and building inspectorates preferred relatively long curing times (to increase safety), contractors preferred shorter times (to reduce costs).[70]

Because the regulations were drawn up by a professional society instead of a State Committee, the regulations could not be imposed upon the sector. In order to make the regulations as generally applicable as possible, KIvI wrote letters to municipalities, ministries, railway companies, and other large corporations with a request to use GBV 1912, and to be informed if there should be comments or criticisms. From the answers it appeared that most addressees already used the draft regulations of 1909 which had been published in *De Ingenieur*. In 1913, the Minister of Public Works officially requested his chief engineers of *Rijkswaterstaat* to use KIvI regulations. Thus, KIvI's GBV 1912 contributed to the institutionalisation of reinforced-concrete technology.

The professional association KIvI thus played a central role in standardisation and production of translocal knowledge. In addition to the GBV Commit-

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[69] Letter to KIvI, dated 21 October 1912 (Algemeen Rijksarchief, KIvI, 1847-1960, Inventory nr. 24, Dossier nr. 36).

[70] When the Committee was asked about the validity of the standards, e.g. for curing times or pressure resistance, the chairman (repeatedly) argued that the members of the Committee were all experts, and their judgement should be trusted. Negotiations had already taken place within the Committee, and did not need to be repeated in the meeting with less knowledgeable engineers.

tee, KIvI's journal *De Ingenieur* had also been an important forum. It was used for announcements, reports, and discussions, e.g. on the reliability of the material and the methods of calculations. Other Dutch journals that paid attention to early developments in reinforced concrete were the *Tijdschrift van het KIvI*, *Technisch Weekblad*,[71] the *Bouwkundig Weekblad*,[72] and the *Bouwkundig Tijdschrift*.[73] Eventually, these journals would be superseded by other specialised journals for detailed discussions on reinforced concrete. Already in 1903, Sanders remarked, after a drawn-out polemic about the coefficient of elasticity for stressed concrete-iron constructions with Rutgers, an engineer of the Rotterdam Public Works department, that he did not consider *De Ingenieur* a suitable journal for polemics on reinforced concrete because its editors were not knowledgeable enough (Sanders, 1903).[74] Specialist journals were a much better forum for polemics. Sanders advised those who wanted to be able to judge controversies adequately, to subscribe to international journal *Beton und Eisen,* edited by Von Emperger. The editors of *De Ingenieur* added in a footnote that they planned to report on *Beton und Eisen* regularly.

While in other European countries the first specialised journals had already been established (section 2), it was not until 1912 that the first Dutch specialist journal on reinforced concrete was published — i.e. in the same year that the GBV 1912 had been published. It was a monthly journal, modelled after foreign journals, called *Gewapend Beton: maandblad voor beton- en gewapend betonbouw*, published by L.J. Veen.[75] Its advertisement read:

> "This specialist journal, which attracts attention in a wide circle, both at home and abroad, gives in an agreeable form important publications of a practical and theoretical nature, illustrated descriptions of executed works, a survey of literature, a report of applied and granted patents, economic and brief general announcement, book reviews, exchanges of opinions, in short everything that is connected with the practice of reinforced concrete.

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[71] Translation: Technical Weekly; published during 1899-1925 by the *Bond van Technici* (Association of Technicians).

[72] Translation: Architectural Weekly; published during 1881-1926 by the *Bond van Nederlandsche Architecten* (Association of Dutch architects) and the *Maatschappij ter Bevordering van Bouwkunst* (Society for the Promotion of Architecture).

[73] Translation: Architectural Journal; published during 1881-1908 by the *Maatschappij ter Bevordering van Bouwkunst* (Society for the Promotion of Architecture).

[74] "I do not consider *De Ingenieur* a journal to engage oneself in a polemic on old points of difference, that some cannot or will not understand. If one wants to take pleasure in that, he should turn to the special journal, but he should leave alone the editors of *De Ingenieur* (a *general technical weekly*) with regard to this disagreeable polemic. The editors, without a special assisting committee, are in my opinion not able to discern good and bad in this matter and for an authoritative and impartial assisting committee it is too early in our small country." (Sanders, 1903; translated from Dutch)

[75] Translation: Reinforced Concrete: monthly journal for concrete and reinforced concrete construction. It was published by the Amsterdam publisher L.J. Veen until 1936 when it fell victim to the economic depression of the 1930s.

> Indispensable for every Engineer, Architect, Contractor, Technician, Student and everybody else that had to do with Reinforced concrete works."[76]

Gewapend Beton aspired to play a prominent role as a facilitator of circulation and aggregation activities in the reinforced concrete sector. One year later, the same publisher, also started publishing the Dutch *Betonkalender* which was modelled after the German *Beton-Kalender: Taschenbuch für Beton- und Stahlbetonbau sowie die verwandten Fächer*[77] that had been established in 1905 (Schippers, 1995). The *Betonkalender* was an annual with technical information on reinforced concrete and its applications. The new journal and annual became part of a specialised infrastructure for further cosmopolitanisation of reinforced concrete technology. In the 1910s and 1920s, this infrastructure would be extended with new forums and intermediaries.

In 1914 it became clear that technological developments had superseded GBV 1912 — which had been created in 1909. For instance, "mushroom columns" had been introduced which did away with the need for beams and joists. New calculation methods were required for these constructions. Contractors that wanted to use new techniques had to deal with customers that were hesitant because these novel techniques were not incorporated in the regulations. Engineers that worked for public works departments and inspectorates had to be covered vis-à-vis their superiors. The regulations needed an update in order to be able to continue to regulate the application of reinforced concrete in practice. As the chairman of the standardisation committee put it:

> The state of affairs with reinforced concrete is as follows. It is something new [sic]; every time new things are added; constantly new requirements are formulated and new constructions are made. Sometimes, that gives cause to difficulties between customers and reinforced concrete constructors, and to differences on the question whether or not something is admissible according to the regulations.[78]

In case of differences of opinion between contractor and customer, GBV 1912 could not always give decisive answers. Rather than to establish an arbitration committee for reinforced concrete, KIvI decided to establish a new permanent standardisation committee to revise the regulations.[79] This time, reinforced concrete contractors tried to get a larger stake in the standardisation process.

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[76] Translated from Dutch

[77] Translation: Concrete calendar: paperback for concrete and steel concrete construction as well as related trades.

[78] Minutes of 26th meeting, 28 November 1914, supplemented to *De Ingenieur*, 1915, nr. 13.

[79] Decision was taken in the 25th meeting, 24 November 1914.

By 1912, the reinforced-concrete sector had grown and counted circa twenty contractors (Everwijn, 1912).[80] Ten of the largest companies had succeeded in forming a collective organisation, i.e. the *Vereeniging van Aannemers van Betonijzerwerken*, also known as the *Betonijzerbond*.[81] The reputed Sanders had become its first chairman. The *Betonijzerbond* was an association exclusively for contractors of concrete-iron works. Its aims were to promote the reinforced concrete trade, and to represent the reinforced concrete industry in matters of regulation and standardisation. The new intermediary actor sought cooperation with KIvI in order to get a role in standardisation. KIvI was reluctant to give up its prerogative because it feared that the *Betonijzerbond* would put commercial interests first, but eventually, the *Betonijzerbond* was allowed to cooperate with the new permanent GBV Committee. The Committee was made permanent because regulations should not lag behind technological developments. The members of the new permanent Committee were installed on 6 February 1916.[82] Chairman was S.G. Everts, professor at the *Technische Hogeschool* Delft, who had been responsible for the first lectures on reinforced-concrete at the Polytechnic school in Delft in 1903. A notable difference with the former Committee was that Sanders and Van Hemert no longer were members. In 1917, the Committee produced new draft regulations which were discussed in two meetings of the KIvI-section for civil engineering. As in 1911, many questions had to do with possible conflicts between customers and contractors, because it was precisely in cases of disputes between customers and contractors that the regulations were consulted.[83] In order prevent arbitration and lawsuits

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[80] In 1912 these 20 companies were established in Almelo (1), Amsterdam (5), Breda (2), Enschede (2), The Hague (2), Leeuwarden (2), Leiden (1), Ouden-Rijn (1), and Rotterdam (4) (Everwijn (1912); referred to by Schippers (1995)).

[81] Translation: Association of contractors of concrete-iron works (a.k.a. Concrete-iron association). Among the ten members were Sanders' *Amsterdamsche Fabriek van Cementijzerwerken (systeem Monier),* Van Hemert's *Hollandsche Maatschappij tot het Maken van Werken in Gewapend Beton* (later: *H.B.M. Nederland N.V.*), the *Rotterdamsche Cementsteenfabriek Van Waning & Co.* (later: *Koninklijke Rotterdamse Beton- en AannemersMij v/h Van Waning & Co. N.V.*), and the *Fabriek voor Cementijzerwerken F.J. Stulemeijer & Co.* (later: *Industrieele Maatschappij J.F. Stulemeijer & Co. N.V.* and, subsequently, *Internationale Gewapendbeton Bouw N.V.*).

[82] The members were prof. S.G. Everts (chair), K. Bakker, A.A. Boon (from the *Amsterdamsche Fabriek*), H.G.A. Treep. Ch. H.J. Driessen, A.C.W. Dwars, W. Hanegraaff, F.C.J. van den Steen van Ommeren, and B.A. Verhey (Minutes of 30th meeting, 15 April 1916, supplemented to *De Ingenieur*, 1916, nr. 27).

[83] For example, former member of the GBV 1912 Committee Van Hemert complained that the rule concerning the number of concrete test cubes of which the mean value had to be determined, was no longer taken up in the regulations. Van Hemert argued that in case of arbitration, one should have something to hold on. In the same vein, he protested against the rule that sand and water might not be contaminated at all. This rule was too strict to be practicable. Again, Van Hemert was afraid that customers could misinterpret this rule. Other discussions were about welds in the iron reinforcement, the execution, the climatic circumstances in which construction had to be halted, the attachment of old to new concrete, the use of hooks at the end of beams, the ways of calculation (for simple constructions), the question whether the regulations concerning calculations only should be applied in case of relatively simple constructions, whether or not to allow theoretical calculations instead of prescribed values, etc. (Minutes of 35th meeting, 23 June 1917, supplemented to *De Ingenieur*, 1917, nr. 48).

the text had to be made as unambiguous as possible. Although the committee did not intend GBV to act as a straightjacket, they did prescribe some restricting rules, much to the regret of contractors. For example, it prescribed only one standard for iron in order to minimise the risks of mistakes in calculations. Contractors preferred a broader choice of materials, but their protests were not included in the final version.

The fact that GBV made credentialed knowledge available was not without risks. It lowered (cognitive) entry barriers which might lead to the entry of *"beunhazen"* or bunglers. Inexperienced and incompetent constructors could get the false impression that they knew what to do — and customers might get the wrong impression that following the rules would be sufficient to guarantee a reliable construction. The GBV Committee was very aware of this risk, and it deliberately did not give many regulations with regard to the calculations. They explicitly included an article to warn that the regulations on calculation should not be applied to complicated systems because these had their own calculation methods. Complicated constructions should be left to the true experts. "Every system needs its own calculation, that should be based on applied mechanics and the outcomes of sound experiments."[84]

> When different plans and designs have come in, and have to be examined and compared with each other, then it is terribly difficult for directorates to compare the various calculation methods that might have been followed, and to come to something that can be chosen. Therefore, for () simple cases moments are prescribed; but one can go no further with the prescription of moments than the simple cases. For constructions that are more complex, one cannot make regulations. In those cases, moments become dependent on the diameter of bodies, on the length of bars, which are connected to each other and on deformings that occur. Every special case must then be inspected separately, and then it pays off to make special calculations. Those who then have to judge those different plans can verify those calculations.[85]

The regulations were explicitly intended for daily, simple constructions, i.e. normal practice. The committee made a distinction between important works, like railway bridges and simple works that occur in the daily building practice. The regulations were intended to be binding only for the building of houses and warehouses that happened everyday. Engineers designing a railway bridge would have take theory — rather than regulations — into account, and make their own calculations.[86] At the time, it was impossible to make regulations for calculations for complicated structures because theoretical developments lagged

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[84] Minutes of 36th meeting, 1 December 1917, supplemented to *De Ingenieur*, 1917, nr. 9; translation from Dutch.

[85] S.G. Everts during 35th meeting, 23 June 1917, supplemented to *De Ingenieur*, 1917, nr. 48, p. 117.

[86] "The principal issue is that we have left out large works, those should be calculated by everyone for himself." (B.A. Verhey during 35th meeting, 23 June 1917, supplemented to *De Ingenieur*, 1917, nr. 48, pp. 119-120.)

behind the technical possibilities. Thus, cosmopolitan knowledge was only limited in scope. As soon as constructions were complicated, local and specific knowledge was required to make reliable designs and constructions. The regulations were meant to be general, unlike, for instance, detailed municipal building police's regulations. The regulations gave guidelines to guarantee a reasonable contract between contractors and customers.[87] If a customer wanted to give further specifications, then they were free to give all the specifications they wanted, besides, or in addition to, the KIvI regulations.[88] After all, the Committee had not been able to take all considerations into account. Too many developments were taking place in the field of reinforced concrete to make all-embracing regulations.

The publication of the new *Gewapend Beton Voorschriften* in 1918 was accompanied by letters to ministers, public work departments, etc. in which KIvI asked for the regulations to be made obligatory. The previous regulations had been adopted by state agencies and other customers and inspectorates, and the same happened this time.[89] As in 1912, reinforced-concrete companies had been waiting anxiously for the updated regulations. For example, *NV Industrieele Maatschappij J.F. Stulemeyer & Co.* wrote to KIvI that it was eager to use the new regulations because that would mean a saving of iron — which had become very scarce and expensive in the Netherlands (and elsewhere) during the First World War. The building inspectorates, however, were not willing to allow a more efficient use of iron, until the regulations had been officially established and published. This indicates that the regulations were expected to function as guidelines. That the regulations were acted on in local practices, is illustrated by the (famous) design of the sanatorium *Zonnestraal* by the architect Jan Duiker. The dimensions of the building were directly related to GBV 1918, which stated that the formwork of floors with a span of 3 m or less might be removed after only one week, while the normal duration was four weeks. Thus Duiker divided floors into multiples of 3 m, in order to save valuable time (Schippers, 1995). Even some minor flaws in the construction could be attributed to GBV 1918. A wrong water-cement ratio had been used, and such a ratio had not (yet) been taken up in GBV 1918.

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[87] Usually, contractors entered their tenders according to GBV. After a contractor was selected a contract was made in which supplementary requirements could be taken up.

[88] When an ignorant local authority prescribed the use of the regulations the situation could occur that experienced engineers could not make innovative designs. This would stifle technological progress. Although this was not the intention of the Committee, it was impossible to prescribe that certain (innovative) constructions could not be rejected. One the other hand, customers were at all times free to reject the regulations as long as they had not been made obligatory by authorities (Minutes of the 36th meeting, 1 December 1917, supplement to *De Ingenieur*, 1918, nr. 9, pp. 138-139).

[89] The regulations were regulations of KIvI rather than of the State, "but experience show[ed] that these regulations [were] adopted by the State, provinces and municipalities". The fact that most executives of technical (public work) departments were KIvI members facilitated adoption (Minutes of the 36th meeting, 1 December 1917, supplement to *De Ingenieur*, 1918, nr. 9, p. 139).

GBV 1918 remained unchanged until 1930 when an updated GBV was published. Also in 1935 and 1940 new GBV's were made and published. While GBV 1912 had been a small booklet with 33 pages, GBV 1940 was a book that counted 117 pages and included tables and drawings (Schippers, 1995).[90]

In 1918, reinforced-concrete technology was further embedded in academic curricula in the Netherlands when J.A. Bakker became the first (part-time) professor for reinforced concrete at the *Technische Hoogeschool* Delft. A new generation of civil engineers was trained which would use this knowledge in practice, and thus contribute to the emergence of a cosmopolitan technological regime. In his inaugural lecture, Bakker addressed doubts about the reliability and durability of reinforced concrete, which still existed within the building and construction sector (Bakker, 1918). He concluded with:

> "So, are reinforced concrete constructions reliable? *My* answers to that is given by my presence here, that I would want to teach the application of a material, in which I myself would not have faith in. I hope that is not expected of me." (Bakker, 1918: 20; translated from Dutch).

As Rutgers, Bakker had been an engineer for the Rotterdam Public Works department. In that capacity, he had learnt to make specifications for reinforced-concrete constructions. He had made many designs himself, but had contracted designing out as well. He had been in the opportunity to assess many different systems, and he used this accumulated experiences in his lectures. He taught his students that only by serious study of the characteristics of reinforced concrete a rational construction could be made. A rational application presupposed the use of applied mechanics, and a thorough knowledge of the materials. He warned his students that it was important to make rational constructions, because human lives were often at stake. In other words, the risks involved provided the rationale for production and use of robust, translocal knowledge. Bakker, and his successors at the TH Delft, taught their students on a wide range of subjects, including static calculations, properties of iron and concrete, methods of reinforcement, effects of chemical influences, changes in temperature. Thus, attention was paid not only to calculations of the strength of constructions, but also to the physical and chemical properties of reinforced concrete, the actual building process, transportation and the processing of building materials. Therefore, the training was sectoral specific, as was the custom at the time at the TH Delft.

After the First World War, when interest in reinforced concrete increased because of shortage of building materials, the *Betonijzerbond* proposed to the Dutch Minister of Agriculture, Industry and Trade to form and finance a committee to do research on the properties of reinforced concrete constructions

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[90] Schippers (1995) refers to A.A. van der Vooren (1940) *Gewapend-Beton-Voorschriften 1940*, Amsterdam: L.J. Veen.

that had been built in the Netherlands so far.[91] This effort was expected to lead to better understandings of, and more trust in, the new technology. Not only contractors were interested in this investigation, but KIvI was interested as well. It agreed to cooperate, on the condition that they got a say in the composition of the committee. A Ministerial Committee was established in 1919 and four years later it published a report in which it was concluded that reinforced concrete was a reliable construction material, if dealt with judiciously (Deknagel, 1947).

Reinforced concrete was increasingly applied in the 1920s. Not only did the recovery of the economy lead to many building activities, it was also a period with an open eye for innovations and new ways of designing and building. Post-war optimism and interest in innovation was reflected in the building sector were reinforced concrete was welcomed with a renewed enthusiasm. Reinforced concrete came to be seen as a modern material, not in the least by modernist architects. In civil and hydraulic engineering reinforced concrete had already gained a good reputation,[92] and now it was increasingly applied in house-building as well (Schippers, 1995). A combination of factors induced municipalities, housing associations, and private contractors to seriously orient themselves on reinforced concrete. Shortly after the war, traditional building materials were scarce and expensive. In addition, there was a shortage of skilled labour, and there was a more stringent control on housing (that led to the rejection of many old houses). Exemplary were housing projects in Great Britain, Germany, and Belgium where economic circumstances had already led to an increased use of reinforced concrete (Schippers, 1995). Thus, the economy of the new building method was a major appeal. The new technology went well with modern approaches to resolve the housing problem, i.e. rationalisation of building, standardisation of materials and uniformisation of houses.[93] Houses had to become mass produced to achieve economies of scale. This required specialisation, accurate planning, and (inter-organisational) coordination. Industrialisation of the building trade was also propagated by modernist architects of

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[91] Algemeen Rijksarchief, KIvI, 1847-1960, Inventory nr. 24, Dossier nr. 36, File "Correspondentie in zake de instelling eener Rijkscommissie tot onderzoek van gewapend beton constructies".

[92] Many works had been realised, such locks, culverts and viaducts. Reinforced concrete bridges were not very suited for the Dutch soil. Only in regions with sandy soils, e.g. in Twente, several arched bridges would eventually be built. Even ships had been built with reinforced concrete because of the post-war shortage of steel (Schippers, 1995: 43).

[93] In order to build enough houses of sufficient quality for the working class, the cost of building had to be reduced. In other industries, cost had been reduced by mechanisation, standardisation and mass-production. The question was if this could also be achieved for the building trade. Because buildings were made on location, mechanisation was not without difficulties. Machines would have to be very mobile and weather influences would hamper an industrial organisation of work. Prefabrication was sought as a solution for these problems. However, prefabrication required much more study and preparation of building than had been the case before (J.P. Mazure, 1947).

"*het Nieuwe Bouwen*".[94] Existing and new reinforced-concrete construction companies took up the challenge to rationalise the application of reinforced concrete. In the 1920s several large council housing projects were undertaken in which various proprietary reinforced concrete systems were used that could be classified in three groups: monolith construction with pouring concrete, assembly of prefabricated elements, and construction with prefabricated hollow concrete blocks (Schippers, 1995; Kuipers, 1987). Major technological developments in reinforced concrete included the use of mushroom columns, multi-storey buildings, pre-stressed reinforced concrete, and precast reinforced concrete. Outside these experiments in large cities, however, reinforced concrete was used in house-building on a limited scale only. When in the 1930s the prices of traditional building materials dropped, reinforced concrete was hardly used anymore for house-building. Only after the Second World War, a new wave of concrete house-building occurred.

As the application of reinforced concrete increased in the Interbellum, several reinforced-concrete contractors took the initiative to establish a new trade association to promote the trade, and to provide guarantees to ensure compliance of contractors with quality standards and regulations. Exclusion of bungling was a matter of enlightened self-interest of bona fide contractors. Reinforced-concrete structures were largely made on location, and there were plenty of opportunities for things to go wrong. Several reinforced-concrete contractors took the initiative to establish a new association in 1925: the *Betonbond*. Its chair was A.A. Boon (who had already demonstrated his cosmopolitan orientation when he published a handbook in 1908 and had participated in GBV 1918). In 1927 the aim of the *Betonbond* was broadened into the promotion of the technology, rather than the trade, and the name was changed to *Betonvereniging* to indicate this change.[95]. In effect, it became an association for the study of reinforced concrete. Other interested parties such as public works departments of large cities could join the club and were given a right to vote. Members in the 1930s included manufacturers, contractors, city councils, private individuals such as civil engineers and architects, and other official and semi-official bodies, such as the *Beton-Aannemers-Bond* (BAB)[96] and the *Bond van Nederlandse Architecten* (BNA)[97] (Sweys, 1967). The *Betonijzerbond* had merged in 1928 with the newly

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[94] The proponents of *het Nieuwe Bouwen* stressed functionality, public health and hygiene. Their slogan was Let light and air enter your house ("*Laat licht en lucht Uw woning binnentreden*"). They willingly used steel and reinforced concrete as modern building materials.

[95] Translation: Concrete association. The change from "*bond*" (union) to "*vereniging*" (association/society) indicates that the association became less an organisation for the promotion of the trade and more an organisation for the promotion of the technology.

[96] Translation: Concrete-Contractors-Association.

[97] Translation: Association of Dutch Architects.

established BAB.[98] The Dutch cement industry (and later also the *Bond van Fabrikanten van Beton(ijzer)waren in Nederland* (BFBN)[99] and the Dutch steel producers) funded the *Betonvereniging* in order to make it possible to do experimental research — which was performed by testing stations (Schippers, 1995). Thus, the *Betonvereniging* became a collective actor set up to enable collaboration and sharing of costs and results of research. Such research was deemed necessary to produce reliable knowledge on new applications and new methods which were developed within the field. To secure a firm position on the cosmopolitan level, it sought cooperation with established intermediary actors like KIvI. It contributed to the infrastructure when it started to publish its own journal *Het Bouwbedrijf*.[100]

The *Betonvereniging* became a key player in the cosmopolitanisation of reinforced concrete. Its official aims included the gathering of data from scientific, technological, and economic fields; the distribution of information (general and specific); the organisation of discussions/reviews and lectures; the stimulation of compliance with the reinforced concrete regulations; and objecting to malpractice where and when this occurred (Binnenkamp, 1990). Thus, the organisation's mission was to contribute to the production, maintenance and distribution of (translocal) technological knowledge, and to stimulate compliance with the rules and standards. Results from its knowledge activities were made available for the whole sector in the form of reports, recommendations, articles, lectures, and booklets for inspectorates. The *Betonvereniging* also organised courses, excursions, and exhibitions. In 1929, for instance, a booklet *Het uitvoeren van betonwerken*[101] was published for a broader public, and in 1930 Y.M.D. Kentie's *Gewapend beton in het gebouw*[102] was published in which a comparison between reinforced concrete and steel was made.[103] Thus, the *Betonvereniging* became active on the cosmopolitan level: it was interested in the technology "as such".

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[98] Initially, the BAB had 27 members and grew to 33 in the early 1940s.

[99] Translation: Association of manufacturers of concrete(-iron) goods in the Netherlands. The BFBN was established in 1922. Members of this association produced various concrete products, e.g. sewer pipes, concrete stones, curbs, ornaments, and slabs for floors and walls, roof elements etc. Some companies had a membership for the BFBN as well as the BAB.

[100] The *Betonbond* (later: *Betonvereeniging*) published *Het Bouwbedrijf* (Translation: the Building Trade) from 1925 to 1933. It was succeeded by *Beton: maandblad, gewijd aan wetenschap en praktijk van het gewapend beton* (translation: Concrete: monthly, dedicated to science and practice of reinforced concrete) that was released in the period from 1933 to 1941 as a supplement of *De Ingenieur*. After the Second World War, the *Betonvereniging* published *Cement* (1949-).

[101] Translation: The execution of concrete works.

[102] Translation: Reinforced concrete in building.

[103] This comparison worked out very well for reinforced concrete. The book included 50 photos and was nicely bound.

The *Betonvereniging* and KIvI increasingly started to cooperate. During the economic depression of the 1930s, the *Betonvereniging* had to abandon its journal *Het Bouwbedrijf*. KIvI came to the rescue, and in 1933 a new journal *Beton* was published as a monthly supplement to *De Ingenieur*. Gradually, the role of KIvI in standardisation and regulation decreased while the role of the *Betonvereniging* in these matters increased. Especially after the Second World War, the *Betonvereniging* would become a pivotal intermediary actor in the reinforced concrete sector. In study groups, technicians and engineers from various organisations collaborated on a voluntary basis.[104]

Indicative of the technological regime that was stabilising was that the *Betonvereniging* started to organise courses for workers, such as concrete carpenters, steel benders and concrete mixers by the end of the 1930s. At the time, reinforced concrete was not taken up in the curricula of the *Ambachtsscholen.*[105] On a higher level, at the *Middelbaar Technische Scholen*,[106] courses in reinforced concrete had been introduced in the 1920s. Many building supervisors and other technicians with mostly supervisory tasks received their education at these schools (Souwerbren, 1990). This helped to create normal practices, guided by cosmopolitan rules as incorporated in handbooks and standards.

In the 1930s, the national government adopted a law which brought into existence the organisation for *Toegepast Natuurwetenschappelijk Onderzoek* (TNO) as part of the national research infrastructure.[107] The idea was to bring existing (and new) sectoral research organisations under one umbrella. This was part of a secular change in which the application of science to technology was increasingly recognised as important. In 1934 the *Nijverheidsorganisatie* TNO was established. The functioning of this organisation was problematic, because several stakeholders (including Ministries with their own sectoral research centres) opposed a centralised research organisation. After several reorganisations, the *Centraal Instituut of Materiaalonderzoek* (CIMO)[108] was established. In 1941, the section Building Materials within CIMO was combined with another TNO working group for concrete and steel construction into the organisation *TNO voor Bouwmaterialen en Bouwconstructies*[109] (Van Kasteel, 1957). As it turned out, the TNO organisations would only begin to function properly after the Second World War.

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[104] In 1967, when the *Betonvereniging* celebrated its fortieth birthday, the chair R.C. Ophorst described the *Betonvereniging* as a study association "in which concrete technicians of governmental agencies, consulting engineering firms and contractors, as well as of education, research laboratories, manufacturers and suppliers, worked together in unison to increase the knowledge of reinforced concrete." (Ophorst, 1967).

[105] Translation: Technical schools.

[106] Translation: Secondary Technical Schools (cf. the current "HTS").

[107] Translation: Organisation for Applied Scientific Research.

[108] Translation: Central Institute of Materials Research.

[109] TNO for Building Materials and Constructions.

During the 1920s and 1930s a standard practice for the design of ordinary constructions had emerged. Education in (technical) schools and universities and a general application of GBV had stimulated the emergence and establishment of a normal design practice. In other countries, similar developments had occurred and similar regulations had been established. The standard practice had become international, thanks to many publications in journals and handbooks, although there were local variations, among other things because of differences in the ratio between costs of material and wages of workers. (Deknagel, 1947).

The emergence of normal design and construction practices was reflected in the fact that reinforced concrete had become a generally applied building material that any contractor of any significance had to be able to apply (Deknagel, 1947). Supervisors and site foremen were considered to be able to have a command of (simple) works in reinforced concrete. Factories, which had started out as simple workplaces that produced mainly tiles and sewage pipes, had evolved in factories that employed engineers and had laboratories to control and improve the quality of concrete. Machines were used for vibrating, compressing, and centrifuging. Indeed, factories in which reinforced concrete elements were fabricated, had been leading in quality improvements. After the war, when prefabrication was identified as a solution for the housing problem, factories got a new impetus (see section 4).

Mechanisation on building sites was limited, although new equipment such as concrete mixers, concrete pumps, tampers, vibrators, etc. had been introduced on building sites as well. Most of these innovations came from the United States, but in Europe and in the Netherlands new methods and equipment were patented. As a result of these developments, the quality of reinforced concrete had been improved. The solidity and density of concrete had been increased — which was important to apply prestressed concrete (see section 4). Nevertheless, little progress had been made with regard to the tensile strength of concrete. Calculations had to be based on the assumption that concrete could have cracks and did not take any tensile stresses. In other words, calculations had to be based on an assumed defect. Such a material could hardly be called perfect from a civil engineer's point of view. Safety margins had to be kept high, and this caused inefficiencies. When, after the war, efficiency was considered to be of utmost importance, research was oriented at avoiding such inefficiencies.

4.4 Post-war developments in cosmopolitanisation

After the Second World War, there was a secular change in which industrial research became recognised as important to improve technology. Governments and intermediary actors began to play a more active role in stimulation of research and the application of scientific knowledge to technological practice. Investments were deliberately aimed at the cosmopolitan level and its infrastructures. In the 1950s, new forums emerged which began to play important roles in the production, maintenance, and distribution of technological knowledge. As a result, the collective knowledge reservoir increased. At the cosmopolitan level, work was done (largely by study groups established by intermediary actors) to study new technological developments and to incorporate them in standards and regulations.

Immediately after the Second World War, the housing problem was acute while the economy was still recovering. To solve the housing problem, industrialisation of building was identified as a solution. On other industries mechanisation, standardisation and mass production had already resulted in considerable cost reductions in efficiency gains. Scientific management, which had been developed in the United States in the 1920s, came to be regarded as a way to improve efficiency. Scientific management aimed to increase the efficiency by studying and analysing meticulously the working methods, and by preparing and controlling systematically the progress of work and the associated costs. Until then, such industrial modes of production and "rationalisation" had scarcely been attempted since buildings were made on location, and building sites were ill suited for mechanisation. Machines would have to be moved continuously. Also the dependency on weather conditions was problematic. Moreover, rationalisation did not meet with much enthusiasm in the building trade, in which already a high degree of specialisation had evolved (Mazure, 1947). The magnitude of the housing-problem, however, stimulated a renewed interest in prefabrication methods. It would save time and cost if prefabricated reinforced concrete elements were transported to the building site to be assembled. The introduction of prefabrication in the building practice would require much more preparation, planning, organisation and coordination (Mazure, 1947). The idea was that standard plans which had been studied in detail had to replace designs for individual blocks of houses. To stimulate the introduction of prefabrication, standard designs should not be allowed to be declared inadmissible by local building inspectorates because of local concerns (Mazure, 1947). The trend towards an industrial mode of production, which was promoted by professional engineers, e.g. within KIvI, created an affordance structure for further cosmopolitanisation.

A new technology which could increase efficiency was prestressing which made reinforced concrete much stronger and allowed savings in materials. It had been developed before the war. In fact, the idea of prestressing had been around since the 1890s when theorists like Koenen had recognised that concrete and iron would form one composite unity, i.e. that shearing would not occur. The French engineer Freyssinet had been the first to point out that high-strength (i.e. expensive) steel was required. In 1928 he had patented his method of prestressing, in which steel wires were stretched in tension, and the concrete was poured around them. After the concrete had dried, the wires were released, and the member would acquire an upward deflection and would be entirely in compression. When the member was loaded, it would deflect downward to a flat position, remaining entirely in compression. A major advantage was that prestressed concrete did not develop the tension cracks that plagued ordinary reinforced concrete. In practice, however, his method was very difficult to apply, and prestressed concrete was not used until after the war, when new building methods were sought. On building sites, the technique of prestressing was difficult and expensive to use because of equipment cost and the expensiveness of high-strength steel. In factories, however, prestressing could be deployed with more ease and there were more opportunities to recover the costs. Thus, there was a synergy between the methods of prefabrication and prestressing.

Immediately after the war, three Dutch contractors joined forces to study prestressed concrete. Soon, several other contractors and concrete manufacturers joined up as well. The group formed a committee to assist the representative of Freyssinet in the Netherlands in matters of licensing. In 1949 several civil engineers decided to set up a group to promote theoretical and practical developments in the field of prestressed concrete. The name they chose for their study group was STUVO.[110] The main goal of the STUVO was the production and sharing of knowledge with regard to prestressed concrete. To that end, STUVO organised congresses, meetings, and excursions. It published guidelines and reports of studies, and it maintained relations with foreign experts (Betonvereniging, 1990).

The production of reliable knowledge on prestressed concrete was important because the performance of prestressed concrete was poorly understood. For instance, there were reports of several cases in which high-strength steel had broken for unknown reasons. In 1952, the STUVO began to do research into this phenomenon which came to be known as stress corrosion. The STUVO also became involved in certification of steel. Producers of steel had to give the mechanical properties and information on the production methods

Meanwhile, the *Betonvereniging* noticed that there was an increased interest in collective research, as was demonstrated by the establishment of STUVO. Before the war, collective research on reinforced concrete had been relatively uncommon. This was partly a result of the fact that the building industry consisted of many small (often regionally active) firms with limited resources to finance research. In addition, there were no large series of products which could justify investments in research. The strict division of design and execution also worked against innovation (Louw, 1967). In 1951, the *Betonvereniging* took the initiative to establish a Fund for Experimental Concrete Research (FEBO) in order to increase the knowledge base on reinforced concrete by means of research. The FEBO was financed by the cement industry (*Stichting Cement Centrale voor Nederland*) and the (reinforced) concrete sector (*Beton-AannemersBond*). Actual research was to be performed by a new organisation, the *Commissie voor de Uitvoering van Research* (CUR)[111] (Scherpbier, 1992). In 1952, the CUR was estab-

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[110] Acronym for *STUdievereniging VOorgespannen beton*. Translation: Study association prestressed concrete.

[111] Translation: Committee for the execution of research.

lished with the mission to initiate and coordinate research, and to take care of funding of this research. The STUVO became part of the CUR.

Research was classified in four subjects: research with regard to theoretical foundations (publications with an orange cover); research with regard to the constituent materials (blue cover); research with regard to constructional applications (yellow cover); and research on constructions themselves (green cover) (CUR, 1955). In its first year, already ten research committees were active within CUR. For instance, the first report published in 1952 was a review of the literature of the "last sixty years" on the composition of concrete mixtures. Many technicians and engineers from industry as well as governmental agencies and universities, volunteered to participate in one or more study-committees (in a personal capacity). In return, they received more knowledge, expertise, experience, relations, as well as status and reputational rewards. On a collective level, broad participation in committees increased the absorptive capacity. Results of research were published in reports of which many became standard works. Research facilities of TNO were used. Every year, CUR-days were organised in which each study-committee gave an account of its results. The results of CUR-days, committee-work, and reviews of CUR-reports were published in *Cement* (the journal of the *Betonvereniging*) and *Beton* (a supplement to *De Ingenieur*). As a cosmopolitan actor, the CUR helped to produce and mobilise knowledge, to make it available for contractors, inspectorates, and customers.

Increasingly, CUR became involved in standardisation and regulation. After 1962 CUR-recommendations were included in the *Gewapend Beton Voorschriften*. Before then, CUR-recommendations, i.e. normative documents which embodied the state-of-the-art, often had anticipated on integration in the GBV. In 1971 a new CUR-committee was established to keep a critical eye on the production of regulations for concrete.[112] It was considered one of the most important CUR-committees. During the 1970s the CUR got more substantial role in the creation of regulations. As the number of subcommittees increased, the CUR was converted into an independent organisation, *Stichting CUR* in 1973. The goals of the CUR remained the same: (collective) production, maintenance, and circulation of knowledge. In 1979, CUR's regulation committee and the *Stichting Commissie Voorschriften Beton* merged into a new organisation, the *Stichting voor Onderzoek, Voorschriften en Kwaliteitseisen op het gebied van beton* (CUR-VB)[113]. From then on, this organisation became responsible for the production of regulations. The name indicates that research is inextricable bound up with standardisation: regulations should be based on robust knowledge.

The 1980s witnessed a broadening of the CUR. Eventually, the CUR would transform itself from a collective research organisation in the field of concrete, into a centre for knowledge management in civil and hydraulic engineering. The acronym CUR was maintained but was given a new interpretation:

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[112] The *Algemene Voorschriften Commissie 'Beton' (AVC-'Beton')*.

[113] Translation: Foundation for research, regulations, and quality requirements in the field of concrete.

Stichting civieltechnisch centrum uitvoering research en regelgeving (CUR).[114] During the 1980s and 1990s, the CUR became a knowledge network in which thousands of technicians and engineers were active. Reinforced concrete technology became only a small part of this elaborate CUR infrastructure. *CUR-Beton* became the part that focussed on research and regulation in the field of (reinforced) concrete. Nowadays, CUR-Beton initiates and guides fundamental and applied research which aims to produce new knowledge on applications of reinforced concrete, characteristics of materials and constructions, and durability. CUR-Beton aims to make this new knowledge available for local practices. If need be, *CUR-beton* translated new acquired knowledge in rules and technical principles.[115] The form and function of CUR's knowledge products varied with the target groups — surveys, tools for policy development, scientific reports, handbooks and guidelines. CUR-handbooks, for instance, acted as a "bible" for those who wanted to get a diploma. Knowledge was also embodied in normative documents, such as protocols, regulations, and CUR-recommendations. These knowledge products were not only used by practitioners in the execution of works, but also by building authorities. CUR-recommendations made new technological solutions acceptable for the building authorities (Van der Steen and Mijnsbergen, 2002). Thus, these normative documents credentialed technological knowledge.

Over the years, the CUR became very experienced in project management, developing research programmes, and collaboration with various knowledge centres. Within the CUR, management of production of knowledge and integration of research, regulation, and knowledge transfer became increasingly important. Especially transfer of cosmopolitan knowledge to local practices was emphasised. Indeed, transfer of knowledge was increasingly recognised as at least as important as knowledge production.

Nowadays, the De CUR describes itself as a unique network of knowledge users and knowledge producers which include contractors, suppliers, regulators, research institutes, polytechnics, technical universities, customers, and consumers.

During the 1950s and 1960s, many study groups were set up, usually under the umbrella of the *Betonvereniging*. There were organisations for the study of prestressed concrete (Stuvo, mentioned before), the study of prefabrication (Stupré), the study of concrete technology (Stutech), and the study of methods and techniques of execution of works in reinforced concrete (Stubeco). Similar associations were established in other countries. Already in 1952 the International Federation for Prestressing (FIP) was established, and in 1953 the European Committee for Concrete (CEB). Both became active in the production, maintenance and dissemination of an international knowledge reservoir on

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[114] Translation: Foundation civil engineering centre for execution of research and regulation.

[115] Website of CUR.

reinforced concrete. They offered forums for international interactions and coordinations and supported an elaborate local-cosmopolitan division of labour.

4.5 In conclusion

The case study has shown how reinforced concrete technology emerged as a heterogeneous set of local solutions to specific problems and was transformed into a standardised, regulated, cosmopolitan technology. In this final section I will address whether this case study has demonstrated the existence of cosmopolitanisation convincingly, and what can be learnt about cosmopolitanisation and the affordance structure. Cosmopolitanisation as I specified it, consisted in the emergence of a cosmopolitan level at which a collective technological knowledge reservoir is produced, maintained, and institutionalised. The emergence of a local-cosmopolitan division of labour and an infrastructure for circulation and aggregation were part of the dynamics.

In the case study of reinforced concrete a pattern in cosmopolitanisation can be identified. In the first phase, which began in the 1850s and lasted until the 1870s, several entrepreneurial producers developed and exploited their local solutions. Their understanding was limited, but by trial and error several producers succeeded in achieving technological and commercial advances. Circulation of technological knowledge was limited and there were few efforts to mobilise knowledge. Indeed, much of the relevant experiential knowledge was protected as trade secret. The applications of what came to be known as reinforced concrete were relatively simple, and *ex post* testing was used to demonstrate the performance. The affordance structure in the early phase was shaped by the enigmatic nature of the configuration. The high variability of materials (sand, gravel, water, iron, etc.) and the large number of potential factors which could influence the performance, made it difficult to reproduce the same performance across time and space. The enigmatic nature of reinforced concrete made it almost impossible for rivals to reverse engineer how the performance had been created. Although the idea of combining concrete and iron was simple enough, patents raised entry barriers for potential rivals. Because of the low level of complexity producers could operate without alignments with other (complementary) producers. The actor-constellation was characterised by several small producers of (usually relatively simple) reinforced-concrete products and a heterogeneous set of customers in niche markets. The degree of interdependency between producers was low, and there were no dominant customers, suppliers or regulators which would induce the production of translocal knowledge. As long as reinforced concrete was perceived as a building and construction technology for small niche markets (e.g. water reservoirs, flower pots, waterproof cellars, etc.) the existing building regime hardly affected technological developments in local practices. In parallel with the emergence of reinforced concrete, professionalisation of civil engineers increased, and professional societies and their forums provided a potentially relevant infrastructure for circulation and aggregation processes.

In the second phase, which begin in the 1870s and lasted until the 1890s, entrepreneurial contractors developed more comprehensive "systems" protected by patents. System owners and their licensees accumulated and exchanged experiences, and achieved a better understanding of their proprietary systems. Hennebique, for instance, created an international network of licensees. To support circulation and aggregation of knowledge, he developed an infrastructure of a journal and conferences. The main office in Paris acted as a centre of calculation. Knowledge production remained system-specific, and circulation beyond the network of licensees was limited. A "battle of systems" emerged in which contractors tried to capture market shares. The situation was fluid, as it was uncertain which system would win and unclear how to determine which system was better. Reputation and advertisement were important. As large customers like Public Works departments, railway companies and the military, and inspectorates increasingly became interested in the new technology contractors disclosed some of their secrets to convince and interest professional customers and inspectorates (cf. "professors of secrets" in the Renaissance). At the same time, some large customers started to produce knowledge themselves to be able to assess the technology independently. Professional engineers could not award contracts to contractors whose designs they could not assess. During the 1870s-1890s the interdependencies between contractors and between contractors and customers increased. The actor constellation created affordances for the production of translocal knowledge when demanding and exacting customers and inspectorates became involved. Acceptance and admission became important to create and expand markets for reinforced concrete. In particular, professional customers demanded reductions of uncertainties and risks beforehand, i.e. before actual construction. As reinforced-concrete constructions became more complex and ambitious, risks and uncertainties increased. For professional engineers who were employed by large professional customers and inspectorates, the way to reduce the risks beforehand was to underpin the technology with data from systematic experiments which could be used to validate theories and calculations. Professional engineers favoured a theoretical and mathematical grasp of the technology, and reinforced-concrete contractors had to take this into account. Some ambitious contractors began to publish in engineering journals and started to develop theories and calculations which could be validated. Sometimes, consulting engineers were hired to assist them in efforts to produce knowledge which would transcend the specificities of particular systems.

The third phase, which began in the late 1890s and lasted until the 1910s, was a period of standardisation and uptake of reinforced concrete in building codes. In several countries standardisation committees were established, whether by the State or by professional societies. The committees tried to establish rules which could be underpinned by theory and data from systematic experiments. The production of the collective good of standards can be understood by the increased interwovenness of contractors and professional customers. For contractors it became counterproductive not to contribute to standardisation activities once they occurred. The acceptability and admissibility of the technology depended on it — as they could experience in practice when potential customers refused to apply a new technology which was not taken up in building codes or when they posed unrealistic requirements. In addition, it was a matter of enlightened self-interest to create rules because collapses (which did occur) discredited the whole sector. At this stage it was unclear whether collapses should be attributed to the technology, poor design or bad execution. Participation in standardisation efforts created an opportunity to influence the outcomes, and it would also offer reputational awards. In practice, additional knowledge production (in the lab mode under controlled circumstances) was done by standardisation committees to generate sufficient data and knowledge to establish rules. Existing experimental findings could not be aggregated because the circumstances under which they had been produced had been too variable. Since reinforced concrete structures were made on location, standardisation of raw materials, and disciplining and supervision of actual execution were important to make standards reliable guidelines. In other words, the practice had to be made similar to the controlled circumstances under which translocal knowledge had been produced.

In the 1890s-1910s, circulation and aggregation activities increased significantly and a collective theoretical-experimental project emerged to which contractors, professional engineers (employed by large customers and inspectorates) and academics contributed. In technical journals an increasing number of articles on reinforced concrete were published. Handbooks were written by experts and intermediary actors in which different systems were compared and evaluated and in which theories and calculation methods were put forward. Technical models were created which could explain the performance in terms of a number of salient variables. Rules for calculation were established. At universities the new technology was incorporated in curricula, which further contributed to cosmopolitanisation. Civil engineers were trained in reinforced-concrete technology, and they would use their knowledge of the collective knowledge reservoir in the practices of their employers. Cosmopolitanisation was facilitated by an infrastructure of forums (e.g. journals, sections of engineering societies, committees). The infrastructure became increasingly differentiated as new specialised journals were introduced and new intermediary actors emerged. Trade associations were established to promote the interests of established contractors, and soon these associations became active in the standardisation of reinforced concrete. The establishment of "good" standards was vitally important for the emergent industry. By the 1910s a comprehensive local-cosmopolitan division of labour had emerged which incorporated contractors, professional customers, engineering societies, trade associations, academics, inspectorates and test stations. Technological knowledge no longer was system-specific, but referred to reinforced-concrete technology as such. The affordance structure for this next phase in cosmopolitanisation was largely shaped by changes in the actor constellation, in particular the emergence of demanding customers and the involvement of professional engineers and academics.

In the next phase, which lasted from the 1920s until the Second World War, a "normal practice" of design and construction emerged and local practices were increasingly guided by cosmopolitan knowledge products. As the fluidity of the situation decreased, the actor constellation changed. Competition between contractors became less fierce, which shaped an affordance structure for further cosmopolitanisation. Contractors sough cooperation to collectively share costs and results of research. In the Netherlands, the *Betonvereniging* became an important intermediary actor in the production, maintenance and distribution of the collective knowledge reservoir. Courses were organised by the *Betonvereniging* as well as technical schools. The standards which had been developed in the 1910s were actually used in practice, and provided a legal framework for both contractors and customers. In the 1920s, after the First World War, reinforced-concrete came to be recognised as a "modern" building material, and it was embraced by modernist architects. Because of its cost advantages vis-à-vis traditional building materials, reinforced-concrete was used in municipal housing projects. Experiments were done to mass-produce houses using prefabrication techniques. This created additional affordances for the production of translocal knowledge because it involved extensive coordination and standardisation. By 1940, reinforced concrete had become a technology which any contractor of any significance had to be able to apply.

After the Second World War, cosmopolitanisation of reinforced concrete reached a new level. It was a time in which industrial research and "applied science" were recognised as important for technological development. Industrialisation, rationalisation, standardisation, and prefabrication were ideographs of the 1950s. In the building trade, these solutions were applied to the huge housing problem which had been created by the war. In the Netherlands, the government subsidised (sectoral) research institutes, and contractors sought cooperation to study prestressed concrete and prefabrication. Study groups were established which eventually came under the umbrella of the *Betonvereniging*. An particularly influential research centre was the CUR, which provided a mechanism for collective pre-competitive production of translocal knowledge. The *Betonvereniging* and its associated associations became prominent actors at the cosmopolitan level. The production of translocal knowledge was international. Research associations and industry associations were part of an international network, and engineers met at international conferences. (Publications of the CUR, for instance, were in English rather than Dutch.) Reinforced concrete became a cosmopolitan technology: a local-cosmopolitan division of labour occurred in which intermediary actors (study and research association and technical societies) played important roles; an infrastructure of journals, conferences, emerged which supported production and circulation of translocal technological knowledge.

I can conclude that the case study of reinforced concrete has given an empirical foundation for my specification of cosmopolitanisation. In addition, the case study suggests that cosmopolitanisation happens in phases. These phases can be labelled as a local phase, followed by an inter-local phase, a trans-local phase, and finally a cosmopolitan phase. During the inter-local phase (1870s-1890s), producers of the technology became increasingly interwoven with other producers, suppliers, users, and regulators. Increased interdependencies resulted in the trans-local phase (1890s-1910s) in a two-level dynamic in which a translocal level started to guide the local level. In the cosmopolitan phase (1920s-present), a reversal occurred in which the cosmopolitan level got a dynamic of its own and local practices became part of a stabilised cosmopolitan technological regime. In the next case study, I will examine whether a similar pattern can be distinguished.

Evaluation of the affordance structure

In my conceptualisation, the affordance structure consisted of three interrelated elements: (1) the historical setting, pre-existing infrastructures and mosaics of regimes; (2) technology affordances; and (3) actor-constellation affordances.

Historical setting, pre-existing infrastructures and mosaics of regimes

The case study of reinforced concrete was deliberately selected because it emerged in the second half of nineteenth century. At that time, cosmopolitanisation was not as widespread as it is today. New technology nowadays often emerges in a context which is prestructured by outcomes previous cosmopolitanisation processes. It is likely that there are intermediary actors which are looking for a role to play in anticipated cosmopolitanisation processes. In general, contemporary actors are more reflexive about cosmopolitanisation, and will anticipate on such socio-cognitive dynamics. In the nineteenth century cosmopolitanisation started with a local phase in which cosmopolitanisation emerged largely “behind the backs” of actors.

Secular developments which created affordances for cosmopolitanisation in the case of reinforced concrete included the (ongoing) professionalisation of engineers. Professional societies with their journals, committees and conferences played an important role in overcoming thresholds. As professionals, they favoured knowledge which could be underpinned by engineering theories and data from systematic experiments. Professionals cultivate specialist knowledge and extensive training, and this was clearly visible in the case of reinforced concrete. Also the changing role of the State was notable. In the Interbellum, and especially after the Second World War, national governments began to actively stimulate industrial research. Both World Wars stimulated a (renewed) interest in reinforced concrete as a “modern” technology to enable “rationalisation” and “industrialisation” of the building trade.

Thus, this part of the affordance structure is relevant for understanding the dynamics of cosmopolitanisation.

Technology affordance

In chapter 2, I argued that the affordance structure on the level of materials is shaped by the impenetrable nature of the configuration. The relation between the performance and the constituent materials and the method of mixing/formulation/processing was anything but obvious. How sand, gravel, water, iron, etc. aligned into a reinforced-concrete structure was difficult to grasp. Initially, producers relied on experiential knowledge, based on trial-and-error learning and testing. Knowledge was relatively easy to protect by secrecy because it was highly contextual and because reverse engineering was hardly possible. The impenetrable nature of the configuration can account for the enormous amount of work various actors put into testing and experimenting. It became vitally important to establish the properties of concrete and iron in order to be able to create translocal knowledge. It also created affordances for standardisation and certification of raw materials which eventually became available in uniform qualities, and for standardisation of executions of reinforced concrete constructions — in particular because constructions had to be made on location under variable circumstances which could not be controlled.

Since reinforced concrete is not a complex technology, this affordance was not present in the case study and cannot be validated. Initially, pioneers could act on their own without alignments with other complementary producers. The application of reinforced concrete is a repeated affair. This created affordances for producers to learn from their experiences. At the same time, however, reinforced concrete structures were largely made on location, which made such learning difficult. Indeed, the high variability of the application contexts was a reason why contractors distrusted cosmopolitan knowledge. When prefabrication was introduced and the conditions under which reinforced concrete elements were produced could be controlled, the affordance structure was raised. The emergence of new modes of collective knowledge production and increased efforts to standardise application conditions in the 1950s and 1960s was enabled by this increased control over circumstances.

The risk of failure also created affordances. Collapses (which could discredit the technology rather than the constructor) contributed to research and study of reinforced concrete and the subsequent regulations. Under the influence of demanding customers and inspectorates, collapses were to be prevented by reductions of risk beforehand, i.e. by producing reliable, reproducible technological knowledge.

Finally, the fact that reinforced concrete is part of larger, more complex configurations, also shaped the affordance structure. As long as reinforced concrete was used for simple artefacts, there were few affordances for the production of translocal knowledge. But when reinforced concrete was incorporated in buildings or large civil engineering projects, the affordances were raised, and demands were made for reinforced concrete to be made reliable and calculable.

In can be concluded that the technological aspects created affordances which were relevant for the understanding of cosmopolitanisation. The role of complexity will be analysed in the case studies of video recording (chapter 6) and air traffic control (chapter 7).

Actor-constellation affordance

In the case of reinforced concrete, the roles of dominant and demanding actors in creating affordance for production of translocal knowledge were clearly demonstrated. In the 1890s, for instance, Hennebique was a dominant contractor. His company did a lot of aggregation work. To create a market, knowledge products were disclosed to convince customers and inspectorates. Also the role of demanding actors was clearly present. In the 1890s, Wayss and Koenen faced a demanding building inspectorate which had to be convinced which more than *ex post* testing. Subsequently, Koenen started to create theoretical knowledge which could be used to calculate the performance. In the Netherlands, *Rijkswaterstaat* and Public Works departments of large cities (Rotterdam in particular) were such demanding customers. They did not want to use the technology until translocal knowledge had been produced which was validated by systematic experiments. Increasing interdependencies between contractors and (demanding) customers/inspectorates were a major affordance for cosmopolitanisation which eventually contributed to a local-cosmopolitan division of labour in which contractors, customers, academics and others participated. The increasing interdependencies between contractors contributed to the establishment of an industry association which further enabled collective action, including research. Once the fluid situation became specific (in particular after standardisation in the 1910s), the affordance structure for reinforced concrete increased as well. It is notable that the collective good of a collective knowledge reservoir was mainly created through the presence of intermediary actors like professional societies, industry associations, research associations, study groups, etc.

It can be concluded that the actor-constellation affordance was relevant for understanding cosmopolitanisation. Especially the role of demanding actors was validated. Also the role of increasing interdependencies was important, which underlines the fact that affordances are dynamic. In addition, the dynamic nature of this affordance structure was also visible: once demanding and intermediary actors became involved, thresholds were overcome.

Taking the three elements of the affordance structure together, it can be concluded that they are interrelated. For instance, “risk” and “demanding customers” were closely related. The same goes for professionalisation as a secular process and the importance of professional engineers working for demanding customers. I will continue to analytically distinguish between technological and actor-constellation affordances because they foreground different aspects of the affordance structure.

Chapter 5.
Paint

"Paint formulation is a matter of intelligent mixing and stirring"[1]

"The art of paint making has become a science"[2]

5.1 Introduction

In chapter 3 I selected paint technology as a case study to create a contrast with the case of reinforced concrete on the level of materials. Based on general insights in paint technology, I had reasons to expect that cosmopolitanisation in the case of paint is slower and less comprehensive than in the case of reinforced concrete.[3] Therefore, a main goal of this case study is to analyse if such a slower rate of cosmopolitanisation can be understood by differences in the affordance structure. Since paint technology is also at the level of materials and covers more or less the same period as the case of reinforced concrete, it can be expected that the actor constellation in particular will offer clues for a better understanding of cosmopolitanisation. In the previous case study I argued that cosmopolitanisation might well be characterised by different (overlapping) phases: a local phase, followed by an inter-local, a trans-local, and a cosmopolitan phase. I will analyse whether such phases can also be found in this case study.

Since paint formulation is an age-old technology, I will start with a short historical sketch. In my analysis of cosmopolitanisation I focus on the twentieth century, also because cosmopolitanisation was very limited before 1900.

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[1] Interview with Winkelaar (secretary of VVVF, the Dutch Association of Paint and Ink Manufacturers) in 1995.

[2] Anonymous (2002) *Encyclopaedia Brittanica Online*, Chicago, IL: Britannica Online.

[3] Illustrative for the limited level of cosmopolitanisation is a remark in the *Chemisch Weekblad* "It seems as though paint is one of the best kept secrets in the chemical industry. If one want to know more about the formulation of paint, hardly anything can be found. Each paint manufacturer does have its own attractive website, which shows consumers that every job has its own type of paint." (Van Galen, 2000: 13; translated from Dutch).

5.2 Case study of paint technology[4]

5.2.1 *Paint technology before 1900*

Paint technology is a formulation technology. In its simplest form, paint consists of pigments dispersed in a vehicle. Already in prehistoric times, paints were used for pictorial and decorative purposes. Paints were used also to coat materials to protect them from rotting, rusting and other forms of deterioration.

The level of cosmopolitanisation before 1900 was characterised by a limited circulation of formulation knowledge between paint formulators which were secretive about their methods and techniques. It was common practice for painters to prepare their own end products in the quiet time of winter, from pigments, oils and resins that they bought from traders and/or mills.[5] Accumulation and dissemination of technological knowledge centred around on-the-job learning and passing on of procedural knowledge and skills from master to apprentice. Technological knowledge was largely local, and each manufacturer used its own idiosyncratic formulation techniques. Knowledge on formulation was largely context-dependent and tacit. It was accumulated over years of experience with specific custom-made products, in specific climatic circumstances which required particular performances, and with specific ingredients which had their own specific properties. Knowledge was created through chance discoveries and trial-and-error learning.

In addition to these distributed local knowledge repertoires, there were experts who wrote handbooks, and who travelled around to offer their services to paint formulators.[6] These experts used their many years of experience with varnish and paint formulation, augmented with their study of other experts' recipe books, to write their own recipes and handbooks. Lambertus Simis is an example of a Dutch master craftsman who became well-known and influential

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[4] In this case study I foreground non-artistic uses of paint — i.e. paints as coatings.

[5] In Medieval Europe, oil-based varnishes and paints had slowly come into use, although mostly for paintings rather than as protective coating. During the Renaissance, oils and resins were increasingly used in paints.

[6] There are various examples of experts and their handbooks. One of the first handbooks in which the process of cooking was described was *Das Werkstattbuch des Johan Arendt Müller zu Quackenbrück*. Other examples of handbooks include Jean Félix Watin' *L'art du peintre, doreur, vernisseur : ouvrage utile aux artistes & aux amateurs qui veulent entreprendre de peindre, dorer & vernir toutes sortes de sujets en bâtiments, meubles, byoux, équipages, &c.* (Paris, 1773; reprinted with minor changes in the 19th century), J. Wilson Neil's *The art, theory and practice of manufacturing varnishes* (London, 1834) and Lambertus Simis' *Grondig onderwijs in de schilders- en verwkunst, bevattende eene duidelyke onderrichting in den aard, den oorsprong, sterkte en zwakte der verwen, olyeteiten, enz., het bereiden, en behoorlyk, of kwalyk gebruik derzelven, ook over het behandelen der werken, huizen en rydtuigen, gladhout- en marmer-schilderen, vergulden, verzilveren en metaalen als mede over het verlakken en witwerken enz.*, (Amsterdam, 1801/1823) (translation: "A thorough education in the art of painting and dyeing, including a clear instruction in the nature, the origin, strengths and weaknesses of paints, oils, etc., the preparation, and proper or improper use of these, also on the treatment of works, houses and carriages, polishing and marble painting, gilding, silver- and metal-plating, as well as lacquering and whitewood works etc.").

in his country by writing down his experience-based knowledge on paint in a handbook (Hallema, 1948; De Boer, 1953). He discussed the various paint ingredients and their origins, various production methods, to which he added his own personal formulation tricks. Handbooks, such as Simis', helped to put knowledge on paint formulation into circulation and contributed to a common knowledge reservoir. At the same time, the interpretation and application of this knowledge was not straightforward but required knowledgeable practitioners. Indeed, the varying quality of materials prevented a mechanical interpretation of recipes and guidelines. Tacit skills and accumulated experiences remained crucial to realise an acceptable performance, especially in seasons when the quality of materials was poor.[7]

While secrecy surrounded paint formulation, travelling experts had to disclose parts of their secrets to create visibility and a market for themselves. In doing so, they contributed to the production of a collective good, a collective knowledge reservoir. The translocality that was achieved, however, was limited. It consisted of empirical know-how. Why or how formulation procedures worked remained in the dark. The effects of temperature, pressure and other conditions that are now known to influence chemical changes, were not known, nor systematically studied. Paint formulation was a craft which relied on skill of eye and hand gained through years of practice and on the job learning. At the same time, paint manufacturers succeeded in producing a remarkable range of useful materials with an acceptable performance. Formulations were adapted to specific contexts in which paints were applied. Formulators had their own methods and tricks of the trade. Formulation products, therefore, were local products. Secrecy was an effective way to appropriate expertise that had been accumulated over the years.

Several operational principles were commonly known. For example, part of a collective knowledge repertoire was that linseed oil's drying quality improved when stored for any length of time. It was also commonly known that linseed oil (as well as other drying oils) could be reinforced by adding resins.[8] The principle of reinforcing was simple enough, but the actual formulation process was complicated, and poorly understood. Through trial-and-error learning processes paint formulators succeeded in realising reasonable performances. Formulation techniques usually included heating of a vegetable or fossil resin,

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[7] An example of a recipe from the handbook by Lambertus Simis (1801) shows that the eye of the expert remained necessary to make a good formulation. It also illustrates the necessity to take into account the variability of the quality of the materials. "4 [decagram] of real gum-copal, and not the large pieces from the white amber, or those that are often sold for it; crush these very fine, sift the crushed [parts] through a sieve, crush the coarse [parts] again, until everything is fine; put it in a bottle with two units of lead rosemary oil, or somewhat less if the gum is only just wet enough to be dissolved; put the bottle in the hot sun or in a warm place, and after 2 or 3 days you will find the gum melted; after that you dilute it with spirits making it brushable; next the bottle is closed for storage." (Quoted in Hallema, 1948: 7).

[8] Examples of natural resins are amber, kauri, Congo copal, and rosin.

adding linseed oil, and cooking the mixture to the desired viscosity, and then diluting it with turpentine. The production process was difficult and not without dangers because of the risk of fire, and it required great skill. Formulators cherished their empirical process knowledge as valuable trade secrets. Rivals could not reverse engineer the formulation methods, and had to rely on their own trial-and-error learning and/or hiring of experts.

The technology of formulation was improved considerably when, around 1800, a new, upgraded drying oil, named "stand oil", came into use. It was a concentrate of linseed oil that was made by setting linseed oil on fire and extinguishing it when the desired consistency had been attained. Since formulation involves heating, it is likely that the process had been invented by paint formulators who accidentally set linseed oil on fire. The method of setting linseed oil on fire was eventually replaced by heating the oil carefully in a boiler. The innovation of stand oil improved the performance of varnishes and paints considerably. The skill of preparing stand oils was much valued. Much experience and skill were required to achieve reasonable performances, not in the least because of the variable nature of the natural ingredients. Experts were sometimes hired for this job, which illustrates that knowledge circulated in embodied forms.[9] Formulators became very skilful in the production of stand oil products, although no one could explain the underlying process (Hallema, 1948). Eventually, stand oils were produced and used in many parts of the world as a result of trial-and-error learning on location, travelling experts, and guiding recipes which were brought in the public domain by experts who wanted to create a market or a reputation for themselves. Much of the formulation knowledge, however, remained tacit and highly contextual.

The innovation of stand oil helped Europeans to emulate the enigmatic Japanese lacquer which was famous for its hardness and brilliance.[10] Its formulation was kept secret from Europeans for centuries, which illustrates the productiveness of secrecy as a means of appropriation. Whereas conventional paints had a streaky and fatty appearance, paints that were made with stand oil produced a much more smooth and shiny coating. In the second half of the nineteenth century, the performance of Japanese lacquer was paralleled by a patented product that consisted of a mixture of pigments, linseed oil, stand oil and natural resins. It was named after its Oriental example, Japan lacquer. It

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[9] In the Netherlands, for instance, English experts were hired. Because of their valuable expertise, they had a much higher social status than the rest of the personnel. Sometimes they even claimed their own canteen — which they were granted, well into the twentieth century (De Vlieger, no date).

[10] In the sixteenth century, the first Europeans to visit Japan were fascinated with lacquer, which was unknown in Europe. They had unsuccessfully tried to find out how it was formulated. The Japanese used a technique in which metal particles, usually gold or silver, were sprinkled onto still damp lacquer to create an image or pattern. The lacquer acted as an adhesive for the metal particles, and when it hardened, the two mediums together created a lustrous, adamantine picture. These lacquer pictures were used on all sorts of objects, varying from small boxes to entire buildings. The lacquer was made from the sap of a tree indigenous to Asia, and the Japanese mastered lacquer making to a degree unmatched elsewhere in Asia.

became widely used for applications were a hard and shining finish was required, e.g. coaches. Other formulators had been experimenting with the same sort of formulation in an attempt to create high-performance coatings for demanding applications like coaches. In the Netherlands, paint and varnish formulators copied the process and began making and selling Japan lacquers in the 1890s, not hindered by patent rights, because no patent law existed in the Netherlands between 1869 and 1912. Japan lacquers were the first to be produced on a more or less industrial scale.

In the nineteenth century, a paint industry in the modern sense of the word did not exist as paints were largely made by painters themselves with materials and semifinished products they bought from their suppliers. On the supply side, industries did exist. There was an international pigment industry.[11] Chemical companies had developed synthetic pigments to complement the assortment of natural pigments, like iron oxide and zinc oxide which were found in the ground. There also was an oil industry which supplied formulators with drying oils. Linseed oil, which was produced in oil mills from flax, had become the dominant vehicle in the eighteenth century.[12] In the Netherlands, an internationally renowned linseed oil industry had emerged.[13] The quality of linseed oil could not be taken for granted. Qualities varied with the season and its origin. In general, the quality of natural ingredients was a unpredictable factor for paint formulators. It was difficult to achieve an uniform quality with variable ingredients.

During the nineteenth century, painters increasingly began to use semifinished and ready-made products. Especially, the labour-intensive process of rubbing and grinding the pigments in oil was gradually mechanised and taken over by paint manufacturers. The rising wages of painters probably accelerated this division of labour. Also the fact that pigments like white lead were a serious health risk became an issue which contributed to this mechanisation. Stand oils were among the first products that could be bought off the shelf. The emergent paint industry was characterised by many small paint manufacturers that were active in regional markets, and that maintained close relationships with their suppliers of raw materials as well as their customers. Paints were usually made to order.

Thus, cosmopolitanisation was limited at the end of the nineteenth century. Much of the formulation knowledge was local and tacit, although there were (guiding) recipes in the public domain. There were many small local practices and circulating experts offering their services. A local-cosmopolitan divi-

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[11] Dutch white lead manufacturers, for instance, dominated the international market from the seventeenth century (De Vlieger and Homburg, 1993).

[12] The earliest vehicles had been prepared from sources such as arabic gum, egg white, gelatine, beeswax and turpentine.

[13] Linseed oil was not only used for paint, but also for linoleum and feedstuffs (Hallema, 1948).

sion of labour did not exist, and the infrastructure for circulation and aggregation was also limited. This is understandable since there were few affordances for cosmopolitanisation. Similar to the case of reinforced concrete, the enigmatic nature of paint formulation made secrecy an effective appropriation strategy. There were no affordances on account of complexity. Since paint is not a constructional material, like reinforced concrete, failure did not have dramatic consequences. If the performance of paint did not meet expectations, the layer of paint could be removed and a new layer could be applied. The production of reliable, translocal knowledge was not induced by requirement from higher-level configurations. Thus, the technology affordance structure was low. Also the actor constellation created few affordances. Unlike in the case of reinforced concrete, there were no dominant customers who took a professional interest in the technology. In a situation with many small manufacturers having bilateral relationships with their suppliers and customers in regional markets, based on bilateral trust, there are few affordances for cosmopolitanisation. At the end of the nineteenth century, however, interdependencies in the actor constellation were changing. This is were the case study of paint technology really starts.

5.2.2 Upgrading of paint ingredients and new demanding customers, 1900s—First World War

In the first two decades of the twentieth century a more systematic mode of knowledge production emerged. This was exemplified by that fact that several paint companies established laboratories to systematically test the performance of paints. Laboratories and instrumentation made formulation and performance more measurable — thus more susceptible for aggregation. At the same time, secrecy remained a productive strategy, and knowledge sharing remained limited. Knowledge development was empirical, based on trial-and-error and accumulated experiences. There were first signs of the emergence of a local-cosmopolitan division of labour when industry associations were formed which provided an infrastructure element which, potentially, could help to create collective knowledge products. Can developments in the affordance structure account for these developments?

In the early part of the twentieth century the actor constellation changed. Suppliers (of oils and resins in particular) increasingly delivered upgraded natural materials with more uniform and predictable properties to a paint industry which served a new range of customers with higher and more varied requirements. The reduced variability of paint ingredients helped formulators to repeat performances, which was especially important for large customers (e.g. automobile industry).[14] On the demand side, industrial production increased resulting in evermore products and constructions which all needed coatings for protection and/or decoration. Not only the quantity, but also the quality of demand changed. Modern artefacts, like automobiles, aircraft, and submarines

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[14] Potentially, reliable and repeatable performance is also crucial for a consumers' market, but a do-it-yourself market did not exist.

required coatings with high performances (in terms of gloss, hardness, durability, drying time, ease of application, etc.).[15] Large industrial and military customers demanded relatively large volumes of paints with uniform, repeatable performances. These demanding customers created an affordance structure for investments in paint technology. Paint manufacturers introduced formulation equipment for grinding, heating and mixing. Mechanisation and instrumentation not only allowed for higher efficiency and productivity, it also offered opportunities for improving control of formulation processes as it reduced the number of (known and unknown) variabilities during formulation. Various paint manufacturers set up small laboratories to test paint ingredients and coatings. Testing became an important means to enable trading relationships with (distant) customers. These laboratories helped to assure qualities and to establish and maintain a good reputation. Attempts were made to make formulation processes and paint performances measurable in order to be able to realise repeatable performances. Whereas customers in the case of reinforced concrete became involved in testing and modelling the technology, customers in this case kept aloof from such knowledge activities. Customers demanded repeatability and uniformity rather than calculability or descriptions of how the performance was achieved. Small-scale experimenting, trial-and-error learning and *ex post* testing had always been part and parcel of paint formulation practices, but under the influence of changes in the actor constellation, accumulation of experiences and findings became more productive and less problematic. A complementary development was the introduction of new storage and distribution technologies which made it possible for paint manufacturers to market their paints in new ways. In the architectural market, paints increasingly became branded products rather than custom-made products. With new storage and distribution techniques, paints could be made in larger quantities, which allowed for economies of scale.

Thus, changes in technology and the actor constellation — partly shaped by secular changes, e.g. industrialisation — contributed to an affordance structure which can account for a limited increase in cosmopolitanisation. Aggregation had become less problematic (due to improvements at the supply side) as well as potentially more productive (due to changes at the demand side). However, interactions between local practices remained limited, and there were few intermediary actors. Secrecy remained a dominant strategy and paint manufacturers employed their own idiosyncratic methods and rules. Within the industry, a wide variety of test methods existed to establish performance characteristics

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[15] Car manufacturers still have high requirements and they only want to buy from certified paint manufacturers. Winfried Kreis of BASF Coatings explains: “Demand for quality has always been high because the products we supply lose their identity later. Buyers shopping for automobiles are not looking for a BASF coating but a certain brand of car. Viewed from that angle it is of course understandable that our customers do everything in their power to make sure that their suppliers do justice to the quality image of their brand. And it always has to be the same, no variance is ever tolerated.” (Flacke *et al.*, 1998).

for paints. Idiosyncratic test methods were unproblematic as long as paint manufacturers had close (regional) ties with their customers. As the market for paints grew and new demanding customers emerged, standardisation of test methods became an issue which was taken up by standardisation organisations. Large customers demanded guarantees that paints met requirements, and this implied measurable and comparable performance characteristics. Standardised test methods were identified as an effective way to regulate trading relations between paint formulators and customers. Standardised test methods reduced transaction costs between paint manufacturers and customers as it became less costly to create contracts. In the United States, for example, the American Society for Testing and Materials (ASTM; established in 1898) set up a Committee in 1902 whose aim it was to standardise the testing and quality control of paints and paint production.[16] In the twentieth century, standardisation of test methods would remain an important issue for the paint industry.

In terms of cosmopolitanisation of paint formulation, standardised test methods did have limited effect. Standardised test methods referred to performance characteristics, rather than the way in which performances were achieved. Therefore, these standardised test methods provided little guidance for paint formulators. Performances could be achieved in numerous ways — indeed, it was largely unknown exactly how performances were realised. Nevertheless, standardisation of test methods contributed to increasing interdependencies between formulation practices.

Increased interdependency between paint formulators was reflected in the establishment of industry associations to protect and promote collective (commercial) interests of the sector. U.S. manufacturers had already established the National Paint, Oil and Varnish Association in 1888,[17] British manufacturers formed the National Federation of Associated Paint, Colour and Varnish Manufacturers in 1896, and German manufactures established the *Verband der Lackindustrie* in 1900. In the Netherlands, paint manufacturers set up the *Vereniging van Vernis- en Verffabrikanten* (VVVF) in 1907. The paint industry was one of the first industries in the Netherlands to organise itself, so its establishment was not something obvious. Quarrels with painters had been an occasion for the establishment of the association. VVVF was used for price agreements and cartel formation (Dingemans, 1957). For the production of translocal knowledge, the establishment of industry associations did not have an immediate impact since these intermediaries were established to promote commercial interests, rather than to play a role in the production and distribution of knowledge. Indirectly, however, these associations provided forums for interaction

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[16] ASTM Committee D1 on Paint and Related Coatings, Materials and Applications.

[17] Before the National Paint, Oil and Varnish Association was established, several local and regional paint clubs had existed. (See website of National Paint & Coatings Association for a history of paint associations in the United States).

and exchange which potentially could lead to increased circulation and aggregation processes.

5.2.3 The First World War and the interbellum period

Cosmopolitanisation reached a new level in the 1920s and 1930s. In the 1920s new intermediary actors came to play a role in the production, maintenance and distribution of technological knowledge, which is indicative for new divisions of cognitive labour. New upgraded and synthetic ingredients (especially resins) were made available by suppliers which improved the formulation process. Also new formulation equipment and instrumentation were introduced. New ingredients and instrumentation offered opportunities for new formulations which could satisfy demands from large industrial customers, such as the automobile industry. The paint industry faced a collective challenge in trying to come to terms with new materials and the way they could be used in formulations. In anticipation of demand for knowledge and research activities, existing and new intermediary actors began offering services to the industry. During the 1920s and 1930s, several committees tried to produce knowledge on materials as such, relatively independent from their application. Reports were made available within the paint industry. This signalled a new (collective) mode of knowledge production. In the 1930s research on a collective level became part of a stabilised division of labour. At the same time, knowledge was largely empirical (know-how) rather than theoretical (know-why).

This new level of cosmopolitanisation can be understood in terms of changes in the affordance structure. Firstly, the First World War and its aftermath affected cosmopolitanisation of paint technology in several ways. Since international trade was brought to a virtual standstill during the war, the paint industry faced severe shortages of materials. To survive and continue production of paints, and to satisfy demands from the military to coat weapons, vehicles, tanks, ships, submarines, aircraft, etc., a general search for substitutes for scarce paint ingredients emerged. Paint manufacturers tried and tested many oils, earth elements and other materials. Necessity became a mother of invention, and inventive formulations were made with unusual materials. The chemical industry tried to develop new materials which could be used in paint formulation. The German chemical industry was particularly active in this search for *Ersatz* (substitute) products.[18] A lead for research on *Ersatz* resins was found in the resinous product from phenol and formaldehyde, of which the technical value had already been described and recognised.[19] The German (coal tar-based) chemical industry succeeded in preparing modified phenol-formaldehyde resins

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[18] The fact that Germany did not have as many colonies as Great Britain and France, also played a role. Rather than to depend on imports of resins and pigments from colonies, Germany tried to become self-sufficient.

[19] It was first described by Adolf von Baeyer in 1872, and it had been recognised by Leo Baekeland in his search for a synthetic substitute for shellac.

that were soluble in drying oils. This achievement opened up new windows of opportunity for the paint industry. Natural resins had always been an uncertain factor during formulation (Van Genuchten, 1996). New resins produced by the chemical industry had uniform properties and made paint formulation more predictable. Oil-modified phenolic resins also allowed for new formulations. Chinese wood oil, an oil with excellent drying characteristics, was found to be working very well with phenolic resins. Chinese wood oil (or tung oil) had always been considered a difficult oil because gelatinisation happened all too easily and because it thickened very rapidly when heated. The novel formulation resulted in a vehicle that had a very good performance in terms of drying time and resistance against water and chemicals (Dingemans, 1957). Especially for tanks, aircraft and submarines, paints based on wood oil reinforced with phenol resins proved very effective. Eventually, when phenolic resins became available in other countries, new formulations were emulated.

Thus, the First World War accelerated the development and introduction of upgraded materials and synthetic substitutes for natural ingredients. The coal tar-based chemical industry had demonstrated to be able to supply new vehicles for paint. Chemists and their experimental methods and instrumentation would became more influential in paint manufacture.

After the war the introduction of new ingredients for paint formulation continued. Large chemical companies became important suppliers of the paint industry as they developed capabilities to create all sorts of materials that proved to be usable for paint formulation. For chemical companies, the paint market was relatively small. Research and development in materials was aimed at plastics, rather than paints. Since plastics and paints had been associated with each other for ages, it was not surprising that it was tried to use new materials for paint formulation as well (Bijker, 1995). Shortly after the war, the chemical industry in the United States succeeded in finding new applications for nitrocellulose in plastics and lacquers.[20] The formulation of nitrocellulose lacquers involved new solvents and driers. Synthetic nitrocellulose lacquers proved to have very good drying characteristics that made them very suitable for the coating of mass-produced goods such as automobiles. In mass manufacture, short drying times were highly important, since this immediately affected the productivity of the assembly line. Spraying techniques were developed that enabled efficient application to automobiles and other products like furniture. In general, developments in materials co-evolved with developments on the demand side. The rise of industrial production created windows of opportunity for new formulations and new application techniques, such as the dip tank, flow-coating or

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[20] Nitrocellulose had been produced in huge amounts during the war (to be used for explosives), and after the war new uses were sought for the enormous stocks of, and production facilities for, nitrocellulose.

spraying.[21] Thus, industrial demand stimulated the development of new formulations with upgraded oils and new resins which were increasingly being made available during the 1920s and 1930s. Chemical companies succeeded in developing alkyd resins, urea-formaldehyde and melamine-formaldehyde resins which could be used in paint formulation. Not only new synthetic alternatives were developed, also age-old products were further upgraded, and made less variable and more predictable. Especially vegetable drying oils, linseed oil in particular, continued to be upgraded. Oil suppliers not only succeeded in developing linseed oils with predictable and uniform performances, but they also developed special oils for different pigments, based on findings that different pigments required linseed oils with specific characteristics. Linseed oil remained the life blood of the paint industry.

While suppliers developed new and upgraded materials, paint manufacturers themselves increasingly deployed machines to increase productivity and decrease the cost of labour (Brunner, 1978).[22] Eventually, various types of mills were introduced by machine manufactures each with its own characteristics and designed for different paints.

While the environment of paint manufacturers was in flux, many small paint manufacturers had difficulty with assessing the opportunities and challenges offered by suppliers and customers. In several countries, paint formulators began to professionalise and set up societies for paint technologists which were to help members with keeping up to date with the latest developments. In the United States, "production clubs" had been established by production managers in paint companies to discuss common problems and challenges. As these clubs grew in size and number, coordination and dissemination of the rapidly growing amount of technical information became increasingly difficult. In 1922, the leaders of several clubs organised a national association, the Federation of Paint and Varnish Production Clubs.[23] Its mission was "to provide for the professional development and education of its members and the industry."[24] To

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[21] The spray-gun had already been introduced in 1907, and in the 1920s it became widely used to coat cars. Its speed was a great advantage of the spray-gun, and it proved especially apt for the application of nitrocellulose lacquers. Nitrocellulose formulations were not ideal to apply with a brush because of the high volatility of the solvents used (Van de Poel, 1998).

[22] As a result of improvements in equipment and mechanisation, labour costs of mixing, 'grinding', and filling, have decreased steadily since the 1920s (Brunner, 1978)

[23] Later the name was changed in the Federation of Societies for Paint Technology (FSPT) and Federation of Societies of Coatings Technology (FSCT), respectively.

[24] See the Website of the (international) Federation of Societies for Coatings Technologies (FSCT).

promote circulation of information and knowledge, it began publishing the *Official Digest* in 1923.[25]

In Great Britain, the demand for external sources of information and knowledge was reflected in the establishment of the Oil & Colour Chemists' Association (OCCA) in 1918. As a learned society, OCCA played an active role in circulation. It published the *Journal of the Oil and Colour Chemists' Association*. Together with the industry association National Federation of Paint, Colour and Varnish Manufacturers (also known as the National Paint Federation, NPF) it began lobbying for the establishment of a Paint Research Association (PRA). The concept of research associations had been introduced by the governmental Department of Scientific and Industrial Research, which had been established during the war to stimulate research activities to strengthen domestic industries vis-à-vis foreign competition. The Department would gave a (small) subsidy if the industry would form and finance a collective research association (Bell, 1976).[26] In anticipation of an increased need for new knowledge, proponents of PRA had argued that is was desirable "to put some scientific muscle into the body of an empirical and craft technology of a long-established industry" (Bell, 1976: 4). Collectively funded (pre-competitive) fundamental research was seen as a modern way to inform the industry of new opportunities offered by new materials, and to improve the competitiveness of the British paint industry.[27] It was exemplary for a secular change in which industrial research became recognised as important for the (national) competitiveness of industries. After several years of lobbying, OCCA and NPF succeeded in persuading paint manufacturers to contribute to the funding of PRA, and in 1926 PRA was founded (Bell, 1976).[28] A new element in the British paint industry's knowledge infrastructure

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[25] The *Official Digest* was renamed in *Official Digest Journal of Paint Technology* in 1963. In 1966 it was renamed in *JPT, Journal of Paint Technology*. In 1976 the journal got its current name: *JCT, Journal of Coatings Technology*.

[26] Varcoe (1974) presented a case study of the UK Department of Scientific and Industrial Research (DSIR), since 1916. The DSIR encouraged "any group of firms associating for the purpose of sponsoring research into problems of common interest and undertaking to contribute to the cost." (23). The Department would match income raised by the research associations from their members. It was expected that research associations would be beneficial for members which were related to each other as supplier and user, or which faced common problems. Duplication of research could be prevented and competitive advantages could be achieved vis-à-vis non-affiliated competitors. "Those in direct competition were expected to contribute because they could not afford such a source of information likely to benefit others. Large incentives were nevertheless necessary." (28). By 1920, 2500 firms belonged to Research Associations. In some industries, Research Associations built on, and sometimes incorporated existing associations. "Examples of (successful) research associations are the Portland Cement Research Association, the Electrical and Allied Trades Research Association, the Cotton Research Association and the Photographic Research Association.

[27] Roon (1985a: 15) comments that "in spite of hanging on to secret practices and recipes, the paint trade embraced the technical and scientific aspect quite early on in its development."

[28] PRA's official name in 1926 was the Research Association of British Paint, Colour and Varnish Manufacturers.

had been introduced which could enable a new mode of knowledge production and play a role in further cosmopolitanisation of paint technology.

After its establishment, PRA commenced doing research on the characteristics of Chinese wood oil (tung oil). Since the war, it had been known that tung oil and phenolic resins could make a very good vehicle with excellent drying characteristics, but there remained many uncertainties and unknowns. It was for the first time that British manufacturers funded research on a material as such, rather than research aimed at finding practical solutions for a specific application. PRA's findings were published in a Technical Report. In 1928, PRA began issuing to its members the *Review of current literature relating to the paint, colour, varnish and allied industries* as well as lists of patents and applications, thereby increasing the circulation of knowledge and information about paint. PRA participated in the creation of standards for methods of colour measurement. Thus, PRA became an important intermediary actor in the British paint industry.

In the Netherlands, the same changes were visible when paint manufacturers tried to come to terms with new materials, new formulations and new applications. Cellulose lacquers, for instance, were followed with interest within the industry association VVVF (Dingemans, 1957).[29] VVVF had been established as a cartel, but after the First World War, price agreements had appeared to be untenable when too many paint manufacturers did not participate and painters refused to do business (exclusively) with VVVF members. In 1927, one year after the British PRA had been established, VVVF succeeded in redefining itself as a collective provider of services anticipating on the fact that individual manufacturers were too small to do (and fund) research themselves. As a collective organisation, VVVF not only intended to assist individual companies in solving their specific problems, but also in creating general insights which could be used throughout the sector. Illustrative of VVVF's anticipation on its new role is the rhetorical question asked within VVVF:

> "Is our knowledge about turpentine and solvents advanced enough? Are we satisfied, if we continually experience difficulties and cannot trace their causes? Do we not experience a need for true science in our businesses, instead of experiential knowledge passed down from father to son.?" (Dingemans, 1957: 7; translated from Dutch).

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[29] In 1927 it was reported within VVVF that a cooperative plant for cellulose lacquers had been established in Germany. VVVF considered what to do with this news. It was argued that cellulose lacquers were a potential threat, but that they were not yet perfect. Main users of cellulose lacquers were automobile manufacturers, and this type of customer did not exist in the Netherlands. For Dutch manufacturers, therefore, cellulose lacquers were of limited importance. Because storage life was limited, cellulose lacquers were not suited for export. The advantage of short drying times was counterbalanced by the need to polish the coating, which would incur high cost of labour. Domestic oil and japan lacquers were considered to be at least as good. Nevertheless, it was considered to be important to be kept up to date with regard to new developments — a small threat could suddenly become a large threat (Dingemans, 1957).

In line with the new service-oriented strategy, a linseed oil committee was established to research linseed oil. Its findings were summarised and published in a trilingual brochure in 1927, which indicates that VVVF intended it for international circulation. It signalled a new mode of knowledge production, in which linseed oils from various sources were systematically analysed and assessed in order to generate classifications and general insights in the quality of linseed oil as such. It was to become one of VVVF's main services to initiate a study or research to clarify recurring problems faced by many of its members. In other words, VVVF became active at the cosmopolitan level as it became involved in the production and distribution of translocal knowledge. Its cosmopolitan role was reinforced when VVVF started organising congresses to promote exchange of experiences and findings and interaction between paint manufacturers in 1928.[30] In the same year the first issue of the association's journal *De Verfkroniek*[31] was published. VVVF also became active in maintenance of a collective knowledge reservoir as it set up a library and started a reference index in order to keep up-to-date and provide a survey of the growing numbers of domestic and foreign publications.

A collectively perceived threat or challenge was posed by introduction of new materials, but also emergence of new applications with different (higher) requirements, growing markets, increased (international) competition, and a general recognition of the importance of industrial R&D, created affordances for the new intermediary role of VVVF as a knowledge producer and disseminator. VVVF aimed not just to provide services to its members, but also to improve the competitiveness of the Dutch paint industry vis-à-vis foreign industries. Precompetitive collaboration and collective financing of research were seen as modern and effective ways of promoting a national industry. In spirit with the times, the editor of *De Verfkroniek* called for a more scientific approach in order to keep up with the international competition.

> "The present day requires more than the knowledge of our ancestors and more than our own experience. It requires scientific guidance. Already for a long time has science been neglected in our industry. If one wishes to keep pace with the first ranks of the international paint industry, we have to break with the methods that have been customary to this day." (Dingemans, 1957: 10; translated from Dutch).

The intermediary role of VVVF in the production, maintenance and distribution of knowledge was not ephemeral, but was augmented and supplemented in the 1930s when new intermediary actors and forums emerged in the Netherlands. In part, the emergence of these new actors and forums can be understood as a reaction to the introduction of new materials and new insights and

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[30] During the first congress the desirability of a sectoral laboratory was discussed. Other items on the agenda included the organisation of trade and industry, the need for common advertisements, and the future of VVVF (Dingemans *et al.*, 1957: 8).

[31] Translation: Paint Chronicle.

findings in chemistry. Polymer science, in particular, offered a new way of understanding and formulating paints.[32] In 1933, the *Bond voor Materialenkennis*[33] set up a new section for chemists interested in plastics and polymer chemistry: the *Kring verf, rubber, asphalt en andere plastische materialen*.[34] In the same year, the *Stichting voor Materialenonderzoek*[35] organised for the first time research which was not directly linked to one company, but was intended for a wider circle of interested parties. Such collectively funded precompetitive research apparently fulfilled a need, as VVVF and others began to lobby for the establishment of a research institute in the field of materials. Eventually, the *Centraal Instituut voor Materialenonderzoek*[36] (with a section for research on paint ingredients and finished products, on test methods and on application methods) was established with VVVF as one of its subsidisers. Meanwhile, on a national level initiatives were taken to create an umbrella organisation for applied scientific research in the Netherlands. Eventually, the *Centraal Instituut voor Materialenonderzoek* was brought under the umbrella of a national TNO organisation.[37] It was not until after the Second World War — when initial resistance from existing (research) organisations decreased — that TNO began to function properly. In the 1950s the paint section of the *Centraal Instituut* would be reorganised into a separate *Verfinstituut* TNO (Dingemans, 1957).[38]

On the eve of the Second World War, paint technology had become more cosmopolitan as new modes of knowledge production were used, new infrastructures for circulation and aggregation had been organised, and new intermediary roles had been established in a local-cosmopolitan division of labour.

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[32] Polymer science had emerged in the 1920s, after the German organic chemist Hermann Staudinger had suggested the existence of polymeric chain molecules, so-called macromolecules.

[33] Translation: Association of Knowledge on Materials. The *Bond voor Materialenkennis* still exists as a professional society that wants to bridge theory and practice, science and industry. It is a meeting point for researchers and technicians from companies and institutes. Its official aims include: improvement of knowledge on materials; platform for materials technology; knowledge transfer (to small and medium-sized businesses); promotion of research; and improvement of professional image. The *Bond* organises open as well as closed meetings, it published research reports, articles and advertisements. It cooperates with the *Nederlandse Vereniging van Verftechnici* (NVVT) and other associations in the field. It publishes the journal *Materialen*.

[34] Translation: Section on Paint, Rubber, Asphalt and other plastic Materials.

[35] Translation: Foundation on Research on Materials.

[36] Translation: Central Institute for Research on Materials. Research of the *Centraal Instituut voor Materialenonderzoek* was divided into six areas: (a) analytical (spectrographic and chemical research); (b) corrosion; (c) wood; (d) metals; (e) physical working group (design, calibration and maintenance of measuring equipment for the other departments); and (f) paint (research on paint ingredient and finished products, on test methods and on application methods) (Thijsse and Piket, 1947).

[37] TNO is the acronym of the *Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek* (translation: Organisation for Applied Scientific Research).

[38] Translation: Paint Institute TNO. Other TNO-institutes were: Metal Institute, Wood Institute, Institute for Building Materials and Building Construction, and the Analytic Institute (Dingemans, 1957).

In addition to effects of the First World War and secular changes, cosmopolitanisation processes can also attributed to emergence of new materials made available by the chemical industry and new markets of industrial customers. For suppliers of resins and other materials, the paint industry was a relatively small market and they had not been interested in research oriented at paint specifically. During the economic depression of the 1930s, however, industrial giants as Du Pont, ICI, IG Farben, and Dow, began looking for new product-markets combinations. Paint came into focus as an interesting market (Van der Most *et al.*, 2000). Chemical companies would be going to play a more important role in the production and distribution of paint knowledge.

5.2.4 Developments in the 1940s-1960s

After the Second World War, cosmopolitanisation entered a new phase. The chemical industry flooded the paint industry with new materials accompanied by guiding recipes, thereby increasing the paint industry's supplier dependence. Pre-war knowledge bases gradually became redundant. Intermediary actors helped paint manufacturers to incorporate new technological developments into their formulation practices. Industry-wide courses were organised to train paint technologists, thereby increasing dissemination of aggregated paint knowledge. Professionalisation of paint technologists increased as professional societies became active in the organisation of meetings and congresses, and publication of trade journals. In addition, standardisation of test methods got new impetus as the paint industry became increasingly international.

As during the First World War, the paint industry faced shortages during the Second World War when international trade was restricted. Before the war, paint manufacturers had depended heavily on imported materials, such as (vegetable) oils, resins, solvents and pigments (Roon, 1985b). During the war, many materials were studied as potential ingredients. In an attempt to reduce dependence on linseed oil, which became scarce during the war, water-based paints were developed. The German paint industry, for example, developed special water-borne coatings for tanks. In Great Britain, the Ministry of Defence became the Paint Research Association's biggest client. One of its tasks was to studied the water-based coatings on captured German tanks. American researchers were the first to succeed in making water-based latex paint with a good performance by using synthetic rubber — which was produced in huge amounts during the war as a substitute for natural rubber. These latexes were a significant improvement of natural rubber latexes which had been developed in the eighteenth century in Europe. The old latexes had experienced many technical difficulties and had never become successful as decorative paints.[39] Because of ease of application (with a paint roller), odourlessness and inflammabil-

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[39] The drying of latex paints was based on the evaporation of water that caused the pigment and the vehicle particles to bond, thereby forming a relatively strong film.

ity, latex paints became popular for interior use, wall decoration especially. In the late-1940s and 1950s, latexes came into widespread use worldwide. Guided by insights from polymer chemistry various synthetic latexes were developed after the war.

The introduction of new materials and formulation methods (again) posed threats and challenges for the paint industry. Latex paints were not the only innovation. After the war, it was demonstrated that paints based on alkyd resins could achieve high performances, with high gloss and durability.[40] The modification of alkyd resins with drying oils which gave alkyds their air-drying qualities and solubility, had been pioneered in the 1920s, but the use of alkyds took off after the war, when much had been learnt about this new synthetic material. It was found out how they could be formulated to specification, and how they could be tailored to many different applications.

The chemical industry made available new synthetic solvents and various new additives. In the 1950s and 1960s these new paint ingredients increasingly replaced traditional natural ingredients. Chemical companies accompanied their new synthetic materials with guiding recipes to help paint manufacturers to change their formulation practices without addressing the challenge of understanding paint formulation in general.

In response to the availability of new synthetic paint ingredients, the British Paint Research Association saw new tasks for itself in helping the paint industry to give new synthetic materials practical appraisal. For instance, PRA carefully followed and reported upon technological developments in the United States, such as latex-paints (Bell, 1976).[41] In the course of the 1950s, the scope of PRA's activities broadened. In addition to performing research for the industry, other knowledge activities, including collection, maintenance, and transfer of paint knowledge, were identified as important. To that end, PRA organised courses in elementary and advanced paint technology. Other activities included the organisation of specialist seminars and symposia.

In the postwar reconstruction era, national governments developed policies to promote domestic industries and national research systems. The idea was to make more effective use of scientific and technological knowledge to increase competitiveness of national industries. In the Netherlands, the establishment of a separate *Verfinstituut* TNO as part of the umbrella (semi-public) organisation TNO, was illustrative of this postwar secular trend. The industry association VVVF, which by 1950 represented 98 percent of the paint industry, became a strong proponent of a more effective use of knowledge (Dingemans,

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[40] Other advantageous characteristics include easy pigmentation, ready acceptance of additives, and low yellowing and cracking tendencies.

[41] PRA's director reported in 1948 and 1951 on extensive American tours in two "American Journey" Bulletins (Bell, 1976: 9).

1957). VVVF argued that it was necessary to reap the fruits of scientific developments, and in an industry consisting of small and medium-sized companies, this could best be achieved through cooperation between paint companies and *Verfinstituut* TNO which had good research facilities and trained staff (Dingemans, 1957). Several members of VVVF took the initiative to establish the *Vereniging Voor Verf-Research* (VVVR)[42] in 1951. It was decided to consider only interested parties for membership to prevent passive free riding.[43] The research agenda was geared to practical, recurring problems in the industry. Research activities of VVVR included assessments of new formulation methods and determination of properties of new materials. VVVR produced technical-scientific announcements, reports, and numerous internal reports of its Technical Committee (Dingemans, 1957). The *Verfinstituut* TNO with its research facilities and expertise, performed contract research for VVVR. Part of the incentive for VVVR members to contribute to a collective knowledge reservoir, was that it offered reputational benefits. VVVR's findings apparently scored well at meetings and congresses of paint technologists in the Netherlands as well as abroad.[44]

Developments in paint technology not only affected the manufacturers of paint, but also its customers. The painting business faced frequent problems with new paint formulations and new pre-treatment. In addition, the painting business' problems were heightened by postwar scarcities of building materials and problems with durability of woodwork, e.g. in house fronts. Members from the paint industry and the painting business succeeded in finding support for the establishment of a *Stichting Verftoepassing* (STV)[45] as a collective actors to produce collective goods in the form of research for the whole sector. STV was founded in 1956 to organise and fund research. The research facilities of the *Verfinstituut* TNO were used to perform research. In practice, STV's research activities were largely pragmatic and practical.[46] Its results were disseminated throughout the sector, thereby contributing to a public knowledge reservoir.

Increased cosmopolitanisation was carried by new infrastructures which emerged in the 1950s. In several countries, learned societies, like the British

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[42] Translation: The Paint Research Association.

[43] One-third of the members of VVVF participated in VVVR. They represented two-thirds of the industry's sales.

[44] At least, this was what a former VVVR member recalled in an interview he gave in 1989 Anonymous (1989).

[45] Translation: Foundation Paint Application

[46] In the 1980s SVT looked back on its activities and found that it had been too opportunistic, reactive, and descriptive. It aimed to become more "programmatic, anticipatory, and explanatory" (Anonymous, 1982).

OCCA, the Dutch *Nederlandse Vereniging van Verf-Technici* (NVVT),[47] the West German *Fachgruppe Anstrichstoffe und Pigmente* (APi) of the *Gesellschaft Deutscher Chemiker*[48], and the *Verband der Ingenieure des Lack- und Farbenfaches e.V.* (VILF)[49] organised meetings and congresses. In 1947, the professional associations of France and Belgium had organised the first international congress of paint technologists.[50] Interactions in international congresses between paint technologists from Belgium, the Netherlands, France, Italy and Switzerland lead to the establishment of an European association of paint technologists, FATIPEC, in 1950.[51] This professional society emerged in a context were paint technologists were anxious to be informed about new developments in materials, formulation and application of paints. FATIPEC intended to provide paint technologists with relevant information and knowledge by making publications and organising meetings and congresses. As a professional society, its business was to professionalise paint technologists and contribute to a collective knowledge reservoir. Its mission was to play an active role in production and dissemination of technological knowledge about formulation, manufacture and application of paints, as well as to stimulate research and (international) cooperation between paint technologists (Website of FATIPEC). FATIPEC was part of an international network of paint associations, including the American Federation of Societies for Coatings Technology (FSCT), the British Oil & Colour Chemists Association (OCCA), and the Federation of Scandinavian Paint and Varnish Technologists (SLF).

Not only learned societies became internationally-oriented, also European industry associations sought coordination in the early 1950s. They anticipated forming of a common European market (in 1957) and decided in 1951 to establish the European Council of Paint, Printing Ink and Artists' Colours Industry (CEPE) as the industry's representative and coordinative body on a European level. Although CEPE's role in knowledge production and distribution was limited, it provided yet another forum for interaction. During the 1950s an active network of European and American paint technologists emerged, supported by institutes, intermediary organisations, journals, conferences and other

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[47] Translation: Dutch Society of Paint Technicians.

[48] Translation: Section of Coatings and Pigments of the Association of German Chemists. The *Fachgruppe* was established in 1947 (Website of Api).

[49] Translation: Association of Paint and Coating Engineers. It was established in 1956 at the initiative of graduates from the *Lackingenieur-Schule* in Krefeld. VILF represented and promoted the technical, economical and social interests of its members. The well-known *Farbe und Lack* is the journal of VILF (Website of VILF).

[50] The FIPEC (Fédération des Industries des Peintures, Encres, Couleurs, Colles et Adhésifs) and IVP (Industrie des Vernis et Peintures), respectively.

[51] FATIPEC is the acronym of *Féderation d'Associations de Techniciens des Industries des Peintures, Vernis, Emaux et Encres d'Impremerie de l'Europe Continentale* (translation: Federation of Associations of Technologists in the Paint, Varnishes, Enamels, and Printing-Ink Industries of Continental Europe).

forums. The increase in (facilities for) circulation was reflected in the world-wide circulation of the German journal *Farbe und Lack*,[52] which had existed since 1893. *Farbe und Lack* informed its readers on developments in science, technology and economics that were relevant for the paint industry. It published reviews from other (foreign) journals, patent reports, and market quotations for paint and varnish ingredients and allied products. With regard to cosmopolitanisation, *Farbe und Lack's* "scientific essays" were relevant, because in these in articles innovative developments in materials, formulation and coating techniques were discussed in detail (Bell, 1976).

VVVF became more actively involved in professionalisation of paint technologists. Technological developments in new synthetic materials and increased mechanisation of the production processes called for different expertise and skills. Intensified international competition (reinforced by the prospective unification of the European market) provided added incentive for VVVF to become actively involved in organising courses for paint technologists at different levels. In the courses at the highest level, experts gave lectures in which the state-of-the-art developments in science and technology with regard to paint were discussed (Dingemans, 1957). As part of the effort, paint knowledge was codified in textbooks and other study materials. Exams were established to certify knowledge acquisition. The courses and exams were also an attempt of the paint industry to offer employees better career opportunities and make the paint industry a more attractive employer vis-à-vis other industries with better training and career opportunities.[53] It signalled a transition from the age-old practice of on-the-job training to centralised training. VVVF's courses contributed an industry-wide circulation of knowledge.

In the 1960s the actor constellation changed as large chemical suppliers began to integrate forward.[54] Several large national coatings companies were bought by multinational chemical groups. As a result, the paint industry became more international and concentrated. After the paint industry had incorporated new synthetic materials and new formulation and application techniques the environmental flux abated. The need for information and knowledge became

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[52] *Farbe und Lack* (1893-1943). Merged with *Farben-Zeitung* (1895-1943) and *Der Deutsche Lack- und Farbengrosshandel*, and *Der Deutsche Farben-Händler*, and continued as *Lack- und Farbenzeitschrift* (1943-1944). The latter was continued in 1944 as *Farbe und Lack: Zentralblatt der Farben- und Lackindustrie und des Handels*, established in 1944 by the *Gesellschaft Deutscher Chemiker, Fachgruppe Anstrichstoffe und Pigmente & Schweizerische Vereinigung der Lack- und Farbenchemiker* (translation: Association of German Chemists, section for paints and pigments & the Swiss Association of Paint and Varnish Chemists.

[53] This is still a major concern of the paint industry. See, for instance, the website of the *Verband der deutschen Lackindustrie*, in which a whole section is devoted to interesting students for a career in the paint industry (Website of Verband der deutschen Lackindustrie).

[54] In general, the whole chemical industry changed in the 1960s as the petrochemical industry supplanted the coal-based chemical industry.

less urgent, also because suppliers increasingly began to accompany their materials with guiding recipes. Vertical knowledge flows between suppliers and paint manufacturers increased. The interest in collective research decreased. Thus, sectoral changes affected the roles of research associations such as PRA and VVVR. In addition, with the abolishment of the British Department of Scientific and Industrial Research in the 1960s, public funding of PRA was restricted and alternative financial resources had to be found.

It is interesting to see how PRA and VVVR attempted to survive the new situation. Members of PRA increasingly expected the research association to be geared to finding practical solutions for their local specific problems, rather than at finding general solutions for fundamental problems (Bell, 1976). A tension between theory and practice had existed since the foundation of PRA, but now, at the end of the 1960s, PRA had to reorient its strategy towards local, industrial needs. Patenting of innovations became more extensive, and publicity beyond the membership was sought for new products and processes. To broaden its financial basis, PRA became an international intermediary organisation, with an international membership (Bell, 1976). PRA's international orientation fitted in the trend of internationalisation within the paint industry. National differences would increasingly be diminished as the paint industry and its customers globalised. PRA's reorientation is illustrative of how the production of collective goods can coincide with a private interest aimed at survival. Cosmopolitan actors have to succeed in convincing local actors of the necessity of cosmopolitan knowledge. In the Netherlands, VVVR did not succeed and was disbanded at the end of the 1960s. Changes in the actor constellation had reduced the interest in a collective research association. By the mid-1960s, post-war scarcity of materials had been lifted, and many felt that the most urgent practical problems had been dealt with. New formulations had been incorporated in local practices. Large paint companies had seen a future for VVVR as an organisation for fundamental research, but other VVVR members were not interested in such long-term research.

5.2.5 Developments in the 1970s-1990s

In the 1970s, the level of cosmopolitanisation began to increase again. In the following years, new modes of knowledge production were organised. Academics were involved in the production and dissemination of paint knowledge. A range of new intermediary actors and forums emerged, which is indicative of an increased level of activities at the cosmopolitan level. Local practices increasingly became guided by knowledge products produced at a cosmopolitan level. For a large part, this increase in cosmopolitanisation was afforded by introduction of new requirements and regulations. Major changes occurred in the environment of the paint industry which created a collective challenge. In the 1970s, the whole chemical industry faced a general concern within society with regard to detrimental effects of the chemical industry on the environment and public health. With regard to the paint industry, concerns were raised by environmental organisations, trade unions and governmental agencies about a number of hazardous chemical substances that were commonly used in paint formulations, such as lead, cadmium, PCB, PCT, and asbestos. Governments prepared to take measures to prohibit the use of several harmful substances (Mol, 1995). Thus, the State began to act as a demanding actor. At the same time, concentration processes had resulted in an industry structure with a limited number of large multinational paint companies complemented by many small and medium-sized companies. In the Netherlands, Akzo Coatings[55] and Sigma Coatings[56] which had been formed as a result of mergers and acquisitions, had become dominant paint manufacturers. This change in actor constellation made collective action less problematic because large companies could be expected to take the lead in organising collective action. Anticipating on governmental regulations, Akzo Coatings and Sigma Coatings urged VVVF to take proactive measures in order to protect the industry's interests in the long term (Mol, 1995). They were concerned that small companies could discredit the whole sector if they would continue to use chemicals that were considered hazardous. At the instigation of its largest members, VVVF established a working group which made an inventory of potentially harmful paint ingredients. Anticipating governmental regulations, VVVF forced its members to do away with a number of toxic ingredients. To ease the pain, alternatives for the banned chemicals, which were developed by Akzo Coatings and Sigma Coatings, were made available within the industry (Mol, 1995). Availability of alternatives was considered to be of vital importance for the success of the ban, thus it was a matter of enlightened self-interest to share knowledge. VVVF members which would continue to used banned chemicals would lose their membership. VVVF, therefore, played an important role in the governance structure of the industry. These developments did not have a direct effect on cosmopolitanisation as knowledge remained empirical and existing formulation practices did not change very much. Nevertheless, the way in which a collective threat was met, is indicative of the capacity of the paint industry to organise collective action. The position of VVVF as a collective actor was reinforced and the government recognised VVVF as a consultative party in regulatory matters (Mol, 1995).

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[55] In 1962, a major paint manufacturer, Sikkens, merged with the Koninklijke Zout Ketjen (KZK), a chemical alliance that had been formed a few years earlier. In 1965 KZK merged with Koninklijke Zwanenberg Organon, followed by a merger in 1969 with the Algemene Kunstzijde Unie (AKU). This new company was called Akzo. In the 1970s, Akzo grew rapidly. The German paint manufacturer Lesonal (established in 1858) and the French paint manufacturer Astral (established in 1855) were bought. Together with Sikkens, these companies formed Akzo Coatings. Akzo Coatings continued expanding by establishing and buying manufacturers in Europe, North America, South America, Asia, and Africa. In 1993 Akzo merged with Swedish group Nobel (est. in 1871), which was specialised in paints and varnishes (Website of Sikkens).

[56] Sigma Coatings had emerged in 1972 after a merger of Pieter Schoen & Zoon (established in the 1720s) and International Coating Materials (ICM), which were both part of the PetroFina group. ICM had been established in 1970 after N.V. Vernis- en Verffabriek, voorheen H. Vettewinkel & Zonen (established in 1821), and Varossieau & Cie (established in 1795) merged to improve their competitiveness. In 1971 ICM was taken over by PetroFina (Website of Sigma Coatings).

Cosmopolitanisation did increase after regulators announced more radical regulations and began to play a similar role as building inspectorates in the case of reinforced concrete. In the 1980s, a new, more fundamental, threat emerged for the paint industry as emissions of volatile organic compounds (VOCs) appeared on the agendas of national governments. The paint industry was identified as a major user of solvents.[57] VOCs were considered bad for the environment and painters' health. For paint formulators this implied that indiscriminate use of solvents would no longer be allowed. This posed a serious problem since it was common practice for formulators to use large amounts of solvents. Solvents had been relatively inexpensive,[58] and most paint systems contained organic solvents in order to obtain viscosities appropriate to the application technology, e.g. brushing, spraying or dipping. Formulations with organic solvents had good performances in terms of ease of application and film-forming characteristics. In fact, in the early 1970s roughly 90 percent of all industrial coatings were solvent-borne (Koleske, 1995). As regulations were announced, the paint industry had to do something about solvent use.[59]

For small and medium-sized companies the announced regulations were unsettling since they did not have capabilities to develop new formulations. For large companies the new requirements also meant an opportunity to increase their competitive position vis-à-vis smaller companies, since they did have the resources to develop alternative paint systems. There also was a collective interest to show a united front vis-à-vis regulators. In the Netherlands, VVVF played an active role in keeping the industry informed and organising precompetitive research to find and develop acceptable solutions (Mol, 1995).

Within the paint industry several alternative paint systems did exist, some more mature than others. Powder coatings, radiation-cure coatings, high solids coatings, and various water-borne coatings (e.g. acrylic paints) had been used in niches for decades. Water-based latexes had been developed during the Second World War and had captured a share of the market for architectural paints. Water-based acrylic paints had been introduced in the 1960s. Powder coatings were known since the 1950s, first in Europe and later in the United States. De-

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[57] In the United States the Environmental Protection Agency (EPA) adopted a "process change approach". EPA did not have the authority to ask paint manufacturers about the composition of paint formulations which made it difficult to assess exactly how much VOCs were used. As a result, limited information was available on specific coating formulations. Manufacturers maintained they were proprietary. Companies that applied the coatings claimed little or no knowledge of the formulations of coatings they bought. "Expressing an allowable emission rate as a physical characteristic of the coating placed irrevocable pressure on the paint and coatings industry to change. No one could foresee how much the industry would be transformed." (Berry, 1995: 33).

[58] The oil crisis of 1973 had resulted in higher prices of solvents, however. Higher prices had not been able to change existing practices.

[59] An indication of the sudden change in appreciation of solvents is illustrated by the fact that the 1972 (13th) edition of the *Paint and coating testing manual* of the ASTM only devoted two pages to air pollution, whereas the 14th edition of 1995 had an entire section on the topic of regulation of volatile organic compound emissions (Koleske, 1995).

velopments in radiation-cure technology dated back to the 1960s. High solids had been developed in the 1970s to economise on solvents. Nevertheless, these alternative systems were hardly able to compete with conventional paint systems, not only because their performances were perceived to be lower, but also because of conservatism in the sector and sunk investments in formulation and application equipment (Koleske, 1995).[60]

Announcement of regulations on VOC emissions gave the development of alternative systems a new impetus. Many more parties became interested in technological developments in alternative paint systems. There was a growing demand for information about alternative paint systems within the sector. Existing industry associations and professional societies tried to inform their members about the state-of-the-art and prospective developments. Proponents of the different alternative systems established their own institutes to promote their technologies. Within the field of powder coatings, for instance, a Powder Coating Institute was formed by the American powder coatings industry in 1981. This institute not only became active in the promotion of powder coatings, but also came to play a role in circulation (and aggregation). Technical conferences and trade shows were organised to promote interaction and exchange of information. The Powder Coating Institute produced a variety of publications, technical papers, and other materials designed to promote the use of powder coating and assist powder coaters on technical issues.[61]

In the field of radiation-cure, similar institutes were established. The RadTech association was formed in 1986 in the United States, and two years later a RadTech association was formed in Europe. Objectives of these institutes included promotion (of the benefits) of ultraviolet and electron-beam curing technology and to give information and assistance to suppliers (of equipment and materials) and users.[62] Thus, infrastructures for circulation were present. At the same time, knowledge production was still very much an empirical, experience-based process. There was no technical model which could guide research into new formulations.

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[60] In addition, alternative systems were perceived to have various drawbacks. Water-based acrylic paints had the drawback that the dry film was thermoplastic, which meant that a coating could not be removed by using heat, but that chemicals were needed which were not environment-friendly. Powder coatings had the drawback that once a coating was made, little could be done to alter or upgrade it. Paint formulators were sceptical, not in the least because their role in the value chain would be diminished, since powder coatings could be sold directly from supplier to (industrial) end-users. Conversion to powder coatings would entail substantial capital expenditures for paint users. In addition, there were many other technical and logistical problems. When radiation-cure technology was first conceived in the 1960s, it seemed to have many advantages. However, when experience with radiation-cure systems accumulated, it became clear that many of the chemicals used were strong irritants and human sensitizers (Koleske, 1995).

[61] More information on Powder Coating Institute is available at its website.

[62] More information on RadTech and RadTech Europe is available at their websites.

A consequence of the anticipated transition from conventional paint systems to alternative paint systems was that conventional formulation knowledge would become largely redundant. Faced with a challenge to develop paints that were more sustainable, simpler and quicker to apply with a high efficiency of materials, and less problematic in terms of safety, health and environment (which coincided with demands from large industrial customers for high-performance coatings), the paint industry tried to interest universities in paint technology to help create new "scientific" paint knowledge. It was expected that such fundamental knowledge (know-why, rather than know-how) would give guidance in the development of alternative paint systems.

For academics, paint had largely remained an uncharted territory. From an academic point of view, paint was considered to be very complex, and it did not fit within disciplinary boundaries — since paint technology involved a combination of organic chemistry, physical chemistry, material science, polymer science, and engineering (Koleske, 1995). As a result, paint had not been considered an attractive subject of research by academics, and paint technology had evolved largely without academic contributions. Since the Second World War, new developments in paint formulation could largely be attributed to suppliers of synthetic resins and other paint ingredients. Academics had knowledge on polymers, pigments, solvents and physical and chemical properties, but all the formulation knowledge resided in the paint industry itself.[63]

The wish to interest academics in fundamental research on paint was also prompted by a need for academically trained paint technologists to perform research in industrial laboratories. Paint companies wanted to interest universities in incorporating paint technology into their curricula. Until then, paint technologists had been trained in-house and, since the 1950s, in courses organised by VVVF. Later, courses in coating technology were also organised by schools for technical and vocational training. Universities, however, had not incorporated paint and coating technology into their curricula. Academically trained chemists and engineers which were hired by the paint industry had to be given further training since paint research required a multidisciplinary approach, and academically trained scientists lacked such multidisciplinarity (Anonymous, 1989).

In the Netherlands, collaboration between the paint industry and universities was sought specifically in the lobby for a subsidised collaborative research programme. In the 1980s, collaboration between industry, research institutes and universities was promoted in science and technology policies in order to reinforce national innovation systems. The Dutch Ministry of Economic Affairs had set up a funding programme called *Innovatiegericht Onderzoeksprogramma* (IOP)[64] which aimed to strengthen strategic research at Dutch universities and research institutes, to meet innovative needs of Dutch trade and industry

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[63] Interview with A.C. Winkelaar (secretary of VVVF) in 1995.

[64] Translation: Innovation-oriented Research Programme.

through a programmatic approach. Subsidiary aims of the funding programme were to develop new fundamental knowledge and expertise, to train researchers; to increase knowledge transfer from universities and research institutes to businesses; to develop networks between institutes and businesses, and alliances with international programmes and networks; to strengthen knowledge infrastructures and form divisions of labour; and to anchor outcomes of IOPs in knowledge infrastructures (De Boer, 1999). In my terminology, IOPs were designed to enhance cosmopolitanisation of technologies.

The Dutch paint industry, represented by VVVF, wanted the government to establish an IOP for paint technology. It was argued that cooperation between paint manufacturers, research institutes, universities and suppliers was required, because of rapid developments in society, science and industry (IOP, 2000). In 1984, after lobbying of VVVF, the Ministry of Economic Affairs decided to fund a preliminary *Onderzoeksstimuleringsprogramma Verf* (OSV)[65] which aimed to find out if an IOP for paint technology (*IOP-Verf*) was feasible and advisable. The study of the OSV can be interpreted as an evaluation of the level of cosmopolitanisation. It was concluded that fundamental understanding of paint was limited. A technological model of paint was lacking: "Knowledge on the relations between performance of paint and the composition of the formulation has been established empirically. The performance has been optimised and raised significantly by 'trial and error'. However, if we want to proceed further, the relation between performance and composition has to be modelled. For that, complementary scientific research is required." (Civi Consultancy, 1989: 9; translated from Dutch). Thus, a technological model was deemed necessary because the paint industry anticipated on new and higher requirements (Civi Consultancy, 1989; Van der Meulen, 1992).[66] Scientific knowledge would help laboratories of paint companies to expand their quality control activities with problem solving and product development activities. The conclusion of OSV was that an IOP-Verf could play an important role in creating a new mode of knowledge production, aimed at creating a technological model of paint (Civi Consultancy, 1989).[67]

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[65] Translation: Research Stimulation Programme Paint.

[66] "An important lacuna in the technical model of paint technologists is knowledge why a certain molecular composition of the paint results in certain performance characteristics. The interaction between the different components is unclear. Only when new paints do not diverge too much from existing paints, this traditional method can be continued with reasonable success. The lack of knowledge became apparent when it was tried to adapt paint to more strict environmental requirements." (Van der Meulen, 1992: 153; translated from Dutch).

[67] In the final seminar on OSV Civi Consultancy concluded that it was of key importance that networks had to be formed within the industry and that interaction and communication had to increase. Paint companies had to become less secretive (Dijkstra (1991).

IOP-Verf was established in 1991 and would run to 1999.[68] In these eight years, IOP-Verf contributed to, and catalysed, cosmopolitanisation of paint technology. In the actual research projects, performed in technological universities, TNO *Industrie* (which incorporated the former *Verfinstituut* TNO) and other institutes, it was tried to develop fundamental insights in the workings of paint. This was a new mode of knowledge production for the paint industry. Academics brought into play new conceptual tools, in which paints were described as colloid chemical systems with certain rheological properties, or as polymer systems which combined an emulsion and a dispersion. Thus, academics introduced a new way of studying paints, which was more detached from daily practice, and which aimed to produce theory-based knowledge. Existing standardised methods to measure viscosity, for example, were considered by academics to be too ambiguous and unprecise to be of much use for fundamental research (Van der Meulen, 1992).[69]

Part of IOP-Verf were many activities aimed at dissemination of research results. In collaboration with the Dutch society of paint technologists (NVVT) meetings were organised. Results were published in "fact sheets", in technical and trade journals, and in an IOP-Verf book (De Boer, 1999). For the industry, an important result of IOP-Verf was that new academically trained research personnel became available.[70] It enabled the industry to continue a new mode of knowledge production which was less empirical and more scientific, and it increased the absorptive capacity for cosmopolitan knowledge. Small and medium-sized companies clearly lacked such capacity, and they were less enthusiastic about the results of IOP-Verf. In order to bridge the gap between universities and smaller companies, it was decided in 2000 to establish an independent Branch Centre for Paints & Coatings. This intermediary actor aimed to make abstract, scientific knowledge relevant for local practices. As such, it contributed to making the local-cosmopolitan division of labour actually work.

On the one hand, cosmopolitanisation had been afforded by concentration within the paint industry. On the other hand, (anticipation on) cosmopolitanisation stimulated further concentration and internationalisation of the industry. Concentration partly was a result of intensification of research activities to find

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[68] IOP-Verf involved sixteen research projects which covered four fields of research: binding agents, dispersal, functional properties, and application and removal of coatings.

[69] "The distance between paint industry and universities was so large that the empirical knowledge of paint technologists could hardly be used in scientific research." (Van der Meulen, 1992: 153; translated from Dutch).
Schoff (1995) claims that "too many coatings tests have become standards because they are easy to run, not because they have good precision, measure basic material properties or replicate field conditions and failures. Changes are occurring, albeit slowly, and more in the research lab than in the quality control lab."

[70] In the IOP-Verf book it was concluded the IOP-Verf had resulted in the emergence of networks for innovative paint research. Dozens of students were trained in such a way that they could strengthen the paint industry (De Boer, 1999).

and make new formulations which could meet new requirements and regulations.[71] Only companies of sufficient size were able to afford research expenditures. In effect, this change in the actor constellation made production of collective goods (e.g. collaborative research) less complicated, since groups with fewer and larger parties have less problems in creating collective goods.[72]

Thus, the increased importance of HSE issues, as well as trends towards more efficient use of materials and products, and emergence of new constructional materials and new requirements of durability and aesthetics to increase acceptance of these new materials, created a situation in which the paint industry was prompted to invest in research and development.[73] In general, research and development activities within the paint industry increased in the 1980s and 1990s. The number of people employed in research departments of the Dutch paint industry increased with sixty percent in the period 1985-1990 (Peterse, 1993), which is the more striking because this was a period in which retrenchment of industrial research laboratories began. Large multinational paint companies like Akzo Coatings and Sigma Coatings intensified their research efforts and hired more academically trained chemists and engineers. Sigma Coatings, for instance, followed a proactive research strategy in order to be able to influence governmental regulations and to strengthen its competitiveness in an internationalised market. It was expected that if one understood chemical and physical processes during formulation and application, then it would be possible to have a more rapid and directed development. It was considered more efficient to build up fundamental knowledge first, as a stepping stone in further research and development.[74] A long-term goal was to use computer models in the design of paints. The notion of "paint engineering" was introduced to un-

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[71] Consolidation was also spurred by increasing pressure on margins because paint markets in Western Europe, North American and Japan matured. Growth could only be accomplished by acquisitions (Van Lede, 2001).

[72] An additional effect of concentration was that multinational paint companies became more prominent in the paint industry which had been dominated by national companies until the 1970s. Multinational manufacturers became actively involved in harmonisation of markets. Representative organisations at international levels came to play more important roles. The European Council of the Paint, Printing Ink and Artists' Colours Industry (CEPE) and the International Paint and Printing Ink Council (IPPIC) got more substantial (coordinative) roles, especially with regard to lobbying for standardisation and harmonisation of regulations and environmental standards. As the President of BASF Coatings put it: "Through CEPE, we have to promote the harmonisation of environmental standards in the EU and worldwide to create a level playing field for the industry." (Löbbe, 2001: 35). It contributed to national regulations on paint becoming increasingly similar.

[73] During the 1980s and 1990s, dominant customers began to demand that their paint suppliers qualified for registration under ISO 9000, the international standard for quality assurance. ISO 9000 emphasises planning, training, testing, establishing and meeting requirements, statistical process control, and continuous improvement. Basically, it provides a structured, disciplined approach to managing processes, and it helps to manage knowledge more effectively within an organisation. Intermediary organisation, such as the PRA, offered services to help paint manufacturers to implement quality systems.

[74] Interview with Peterse (R&D manager at Sigma Coatings) in 1996.

derline a departure from "old ways" (Valkema and Zegers, 2000). If the relation between performance and composition would be better understood, better and less complex formulations could be made which were more environmentally friendly, had a higher performance, or were cheaper. The supplying chemical industry was actively involved in development of new paint systems. Resin producers organised courses for paint formulators. The resin producers let their experts, the so-called application employees, circulate through the paint industry to help with formulation problems and production equipment (Mol, 1995).

To take the Netherlands as an example again (and with good reasons, because it was at the forefront of developments), the new approach had further implications for industries. Part of IOP-Verf's contribution to further cosmopolitanisation was that it stimulated incorporation of paint technology in curricula of Dutch universities. In parallel with IOP-Verf, a post-graduate course in coating technology was organised by the institute *Polymeertechnologie Nederland* (PTN) in 1992. Backed by the Dutch polymer industry, PTN was a collaboration between several universities and TNO *Industrie*, established, among others, to promote the role of academically trained researchers in paint technology.[75] PTN's course was based on collated knowledge and expertise accumulated over the years by paint companies and knowledge institutes.[76] Experts from the paint industry as well as university teachers provided training. The course contributed to cosmopolitanisation because it increased the distribution of aggregated knowledge, and increased the absorptive capacity of the paint industry for cosmopolitan knowledge. Participants included chemists, physicists and mechanical engineers who worked in the field of coatings R&D. In 1995, when IOP-Verf was halfway completion, ties between industry and universities were further strengthened when a chair in, and a laboratory for, coating technology were established at the Technische Universiteit Eindhoven. The chair and laboratory were sponsored by industrial parties, organised in PTN.

Involvement of academics in paint technology gained momentum when the Dutch Polymer Institute (DPI) was established as a *Technologisch Topinstituut* in 1997.[77] One-third of DPI's budget was allocated to research in the field of paints and coatings. Research was aimed at developing novel coatings concepts

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[75] Involved universities are TU Delft, TU Eindhoven, University of Groningen, University of Leiden, University of Twente and Wageningen University.

[76] More than 400 students from almost 125 companies participated in the first ten editions of the course Coating Technology (Website of PTN).

[77] DPI was one of four Technological Topinstitutes, which were established by the Dutch government to stimulate the national research system. DPI is a public-private-partnership between industrial parties (AKZO Nobel, Dow Chemical, DSM, General Electric Plastics, Montell (now Basell), Océ, Philips, Shell and TNO) and several Dutch universities. It was established for a period of four years. After a positive evaluation in 2001, the Ministry of Economic Affairs decided to fund DPI for a second period of six years. DPI has become increasingly active outside the Netherlands. The Universities of Hamburg (Germany), Naples (Italy) and Stellenbosch (South Africa) joined DPI (Website of Dutch Polymer Institute).

based on fundamental knowledge as well as analytical tools in order to help partner companies to develop new and sustainable products and/or improve existing coating processes.[78] The establishment of DPI reflects the emergence of a new mode of knowledge production in which a technological model of paint plays an important role. Whereas until the 1970s most research was practical and solution-oriented, the last decades research became more oriented at improvements and innovations.[79] Innovation-oriented research entailed high risks, and these risks were reduced by applying for subsidised research programmes, or by seeking collaborations, e.g. through intermediary actors such as DPI or the Paint Research Association (PRA) in the United Kingdom. Afforded by new requirements and changes in industry structure, collaboration in (fundamental) research increased significantly during the 1990s (Bancken, 1999).

In Great Britain, cosmopolitanisation was exemplified by a new role of the Paint Research Association in the local-cosmopolitan division of labour. In the mid-1980s, anticipating new paint systems which would be needed to meet new requirements, fundamental research became a priority for PRA.[80] By then, PRA had become a large independent knowledge institute in the paint sector. Membership of PRA was open to all coatings related businesses including coatings manufacturers, raw material suppliers, other research associations, equipment manufacturers, end users of coatings and consultants. PRA's technical interests cut across the entire coatings chain — from raw material suppliers and paint manufacturers to applicators and end-users. PRA underpinned its activities by a desire to enhance scientific understanding and to contribute to development of a technological model of paint. PRA not only was a significant locus for knowledge production, it also contributed to collaboration of paint companies in research and to dissemination of knowledge by organising conferences and courses, and publishing a range of journals and other media. In response to internationalisation and concentration in the paint industry, PRA became an international, rather than a British, intermediary during the 1990s. Thus, PRA was a carrier and stimulator of cosmopolitanisation, not only producing cosmopolitan knowledge, but also by disseminating it internationally, intermediating

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[78] Research was performed by the universities of Amsterdam, Eindhoven, Twente, and Wageningen and at the TNO Institutes for Industrial Technology, Physics and Food Technology. DPI's coatings programme is multidisciplinary in character, linking polymer synthesis, colloid chemistry, material science, application technology, analytical chemistry and modelling to product- and application properties. The portfolio contains projects on powder and waterborne coating concepts, on relation between crosslink density versus mechanical and adhesion properties, self-stratification of coatings, UV- and thermal dual cure systems, thermoreversible crosslinks and transfer of liquid and solid particles from spraying devices to substrates (Website of Dutch Polymer Institute).

[79] Twenty years ago, Akzo Nobel Coatings spent 90 percent of its R&D budget at solution-oriented research, 7 percent at improvement-oriented research, and 3 percent at innovation-oriented research. In 2000, these percentages are 50, 30-40, and 10-20, respectively (Bancken, 1999). Bancken was research manager at Akzo Nobel Coatings until mid-1999. He became professor at the TU Eindhoven at the department of civil engineering. He participated in several committees of IOP-Verf.

[80] More information available at website of PRA.

between local practices and a growing cosmopolitan knowledge reservoir. The overall trend is characterised by internationalisation of the paint industry and cosmopolitanisation of paint technology. Illustrative is the institutionalisation of industrial coating technology as an “engineering discipline” at the level of a European engineering society.[81]

5.3 In conclusion

In this case study of cosmopolitanisation of paint technology different overlapping phases with different levels of cosmopolitanisation were identified. The first level of cosmopolitanisation existed before 1900 and was characterised by circulation of experts, handbooks and guiding recipes based on accumulated experience. Knowledge was primarily know-how. Large parts of formulation knowledge were local and tacit. Formulators kept their experiential knowledge secret, and circulation was limited. There were few forums for interaction and exchange, and there were hardly any intermediary actors. This low level of cosmopolitanisation could be understood by a low affordance structure. The combination of the enigmatic nature of formulation, variable natural materials, low complexity, low risk, many small producers without a dominating or demanding actor, did not contributed to an affordance structure for the production of translocal knowledge.

At the end of the nineteenth century, things started to change and cosmopolitanisation increased (slightly) before the First World War. An industrial mode of production was introduced and machines were increasingly used to formulate paints. Industrial laboratories were established to perform tests and (small-scale) experiments with formulations (based on simulation of real-life conditions). The emergence of industrial customers which required larger quantities of high-performance paints created an affordance fur such investments. Standardisation of test methods became an important means to regulate trade relationships. Suppliers began to produce upgraded materials which made paint formulation more predictable and made the enigmatic nature less problematic. The increased level of interdependency within the paint industry was reflected in the establishment of industry associations. Their role in the production and circulation of knowledge, however, remained limited as they focused on commercial interests.

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[81] In 1996, of the *Europäische Gesellschaft für Lackiertechnik e.V.* (EGL) (translation: European Association for Coating Technology) was established. EGL is based on membership of individual persons. The rationale behind its foundation was that industrial coating technology had developed into an “engineering discipline” with many high-tech features in a relatively short period of time. Materials, processes, plants, and test methods were subject to fast changes. The founders of the EGL considered that these developments increased the need for specialists in the coating sector to be well informed, have a good overview, know other specialists, and to have access to a professional organisation for industrial coating technology. The EGL focussed on the correlation of paint material, process technology, and application. The EGL was open to specialists from Europe (Website of EGL).

After the First World War, cosmopolitanisation increased. New intermediary actors became active in a local-cosmopolitan division of labour. Their emergence was induced by technological, sectoral and secular changes which challenged existing practices of paint formulation. Industrial customers, such as manufacturers of cars, aircraft, consumer goods, etc., required uniform high-performance paints. New synthetic and upgraded natural materials made such (repeatable) performances feasible. An important secular change was the recognition of the importance of industrial research by national governments and industrial actors themselves. The establishment of the British Paint Research Association and the changing role of the Dutch VVVF as a collective service provider, were indicative of an increase in collective production and circulation of technological knowledge. These intermediaries enabled collective action in the production of knowledge on materials, formulation, and application, which were made available to the members of these associations. They organised meetings, conferences and published journals, brochures and surveys to stimulate knowledge flows.

This new level of cosmopolitanisation was further raised after the Second World War, which was a period characterised by a general effort to apply science in industry. There was a large demand for paints for many applications, and this allowed for research expenditures. At the same time, the chemical industry started to flood the paint industry which a range of synthetic materials (many of which had already been developed before the war). The environment of the paint industry was in flux, and intermediary actors came to play guiding roles. Professional societies became increasingly active in production and dissemination of paint knowledge, especially on the level of paint ingredients. Collective research came to be seen as a modern way to provide the industry with information and knowledge — also under the influence of governmental science and technology policies which promoted collaboration and the use of scientific knowledge. In the Netherlands the VVVR was an example of a research association. Industry association started to coordinate their strategies in international associations. They also broadened their activities as they became involved in organisation of courses for paint technologists. This more elaborated local-cosmopolitan division of labour is indicative of postwar cosmopolitanisation, induced by secular, technological and sectoral changes. In the 1960s the actor constellation changed as chemical companies began to integrate forward in the paint industry. It was the beginning of a trend towards concentration in the paint industry. At the same time, supplier dependence remained high as many new technological developments came from resin manufacturers.

In the 1970s and 1980s the paint industry was challenged by health, safety, and environmental issues. National governments began to act like a demanding actor which induced innovation. Especially regulations on VOC emissions were so stringent, that conventional solvent-based paint systems had to be abandoned. Existing knowledge repertoires were of limited use in developing alternative paint systems. In effect, governmental intervention not only induced innovation but also created affordances for a new mode of knowledge production. A new level of cosmopolitanisation emerged which was characterised by efforts to model paint, i.e. to elucidate the enigmatic nature of paint formulation. New regulations were seized as an opportunity by large paint companies to involve academics in paint technology. In the Netherlands, which by then was at the forefront of cosmopolitanisation, the paint industry succeeded in convincing the government to subsidise an innovation-oriented research programme (IOP-Verf) which involved several universities. They also backed initiatives to set up a chair in coating technology and a laboratory. Increasingly, paint technology became part of curricula of universities, making available academically trained paint technologists to contribute to "paint engineering" within industrial laboratories. Paint technology started to become "scientised". The creation of a technical model of paint was recognised as a way to make paint technology less empirical and to make R&D more directed and effective. The new level of cosmopolitanisation was carried by an (international) local-cosmopolitan division of labour and an extensive infrastructure of intermediary actors and forums.[82]

In the case of reinforced concrete a four-phased pattern was identified with a local phase, followed by an inter-local, a trans-local and a cosmopolitan phase. A similar pattern was present in the case study of paint. The local phase lasted until the First World War. After the war, interdependencies in the actor constellation increased, and collective/intermediary actors were established. This signalled a shift to an inter-local phase in which interactions and exchanges increased while formulation knowledge was still largely tied to local practices. The third, trans-local phase emerged in the 1980s, when producers identified (collaborative) research as a means to create a technical model of paint which could orient further knowledge production. A local-cosmopolitan division of labour became more elaborate and infrastructures for circulation and aggregation increased. The fourth, cosmopolitan phase has not occurred (yet?). In this phase, the cosmopolitan level gets a dynamic of its own, and a reversal takes place in which local practices become enabled and constrained by the cosmopolitan level.

A major difference with the case of reinforced concrete is the slower rate of cosmopolitanisation in the case of paint. This difference can be explained by taking the different (developments in) the respective affordance structures into account. In the case of reinforced concrete, the (early) presence of a demanding customer accelerated cosmopolitanisation. In the case of paint, such demanding customers were not present. There were large industrial customers, but their demands were for uniform and repeatable performance, not for (calculated) anticipated reliability. I.e. large industrial customers were dominant (e.g. car

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[82] See, for instance, the 'European Coatings Net' on the Internet (www.coatings.de) for an overview of numerous organisations and institutions active in paint technology nowadays.

industry), but not demanding in terms of how the performance of paints was achieved. Trading relations were regulated by standardisation of test methods, rather than standardisation of formulation practices. The absence of demanding customers coincided with a low level of risk. Unlike reinforced concrete structures, paints do not play a constructive role in configurations, and failure does not pose immediate risk of failure — although premature rusting and rotting can impose a major cost. Only in the 1980s regulators began to play a "demanding" role which induced innovations and production of translocal formulation knowledge.

Another notable difference is the supplier-dependence of paint formulators. Major technological developments were initiated and carried by suppliers (for whom paints were only a small market). Paint formulators were reactive, and tried to develop and incorporate new synthetic materials on a trial and error basis with the help of guiding recipes of suppliers. In the case of reinforced concrete, contractors were less dependent upon their suppliers, as sand, gravel, iron, etc. were commodified and the composition of reinforced concrete remained largely the same over the years.

Since reinforced concrete and paint are both on the level of materials in the technical hierarchy, technological affordances were largely similar, although the level of risk in the case of reinforced concrete was much higher. The enigmatic nature of both technologies created similar affordances. In both cases the standardisation of raw materials contributed to a better control over the formulation process. In the case of reinforced concrete, contractors made structures on location, which made it difficult to control the eventual performance. In the case of paint, formulations could be made in factories to be sent out to customers. This created affordances for standardisation and making performance uniform and repeatable. Paint companies used tests in which real-life application conditions were simulated to anticipate on the application contexts. Once demand for paints in certain market segments was sufficiently large (and adequate storage and distribution technologies were present) it created an affordance to achieve economies of scale. Test laboratories were established to create robust and repeatable performances.

Since both case studies occurred in the same period, secular developments created similar affordances. After both World Wars, for instance, the State developed science and technology policies which stimulated industrial research and alignment between the realms of technology and science. It is remarkable that professional engineers played a prominent role in the case of reinforced concrete, while their role in paint was much less important. While reinforced concrete became an engineering technology, embedded in engineering theories etc., paint remained a "traditional" technology. The case study showed that there were attempts to professionalise paint technology, but the process was much slower and had much less impact on cosmopolitanisation. Only recently, the notion of paint engineering has occurred which is used to indicate efforts to model paint formulation. The limited role of professional engineers (compared with reinforced concrete) can related to the non-constructive role of paint.

For a long time, paint technology was a craft. In the twentieth century it became a somewhat systematised craft with characteristics of industrial production. This case study has shown that this level of cosmopolitanisation can continue to exist when it is not challenged. 'Scientisation' of paint technology was not obvious, but only emerged when the affordance structure increased. When affordances do increase, the case study of paint suggests that there is an epistemological sequence in (industrial) research. Before 1900, there was hardly any research, other than knowledge activities by circulating experts and *ad hoc* ("on line") trial and error and testing activities by local formulators to create trust in bilateral relations with their customers. After 1900, research activities emerged which were mainly aimed at establishing test methods to control quality and assure performance. Test methods were eventually standardised at the industry level. In the third phase, which emerged in the 1980s in the case of paint, research efforts were aimed at the creation of a technical model of the configuration (formulation). Systematic experiments were done to clarify the enigmatic nature of paint formulation. In the final phase, which emerged only recently, research is also aimed at the design of configurations. With the help of a technical model, it is tried to use customer requirements as direct input to design a formulation. Epistemologically, there first was an improved trial-and-error/circulation of knowledge mode of knowledge production in which tests on performance ("working") were used as a check. *De facto* standards were established which were supported by analytical methods. This mode of knowledge production was followed by a detour-through-the-lab mode of knowledge production aimed at understanding how and why the configuration works. First, structure-function relationships were established (e.g. which components of a molecule are functional in producing certain colour effects). These could be used as heuristics in design (synthesis). The effort to create a technical model on the level of paint ingredients in the form of a structure-function relationship was carried by chemists, largely in supplier companies. Later, research was aimed at finding a technical model on the level of paint formulation in which the interactions between ingredients and the processes during formulation and application could be modelled. This much more complex modelling effort was part of the emergence of paint engineering.

Chapter 6.
Video recording

6.1 Introduction

In this chapter cosmopolitanisation of magnetic video tape recording technology will be described and analysed. The case study was selected to create a contrast with, and complement, the two case studies on the level of materials. The historical setting, technological and actor-constellation affordances are different. For one, video recorders are very sophisticated artefacts which were developed in the field of electrical engineering which was a highly professionalised and cosmopolitanised world. Typical for a R&D-dependent innovation pattern, engineers working in industrial laboratories of electronics firms were major knowledge producers. In addition, it will be interesting to see how interoperability requirements affected the production and sharing of knowledge. To what extent did anticipations on network externalities, standardisation and (mass-)-markets shape the dynamics? In the case study I will focus on how technological knowledge, which was largely produced in the labs of rivalling electronics companies, became shared and part of a collective engineering knowledge reservoir.

Magnetic video tape recording emerged in the 1950s, at the cross-roads of developments in television technology and magnetic audio tape recording. Since the first video tape recorders built on audio tape recording, I will start the case study with the introduction of magnetic audio tape recording in the electric engineering community in the United States.

6.2 Cosmopolitanisation of magnetic video tape recording technology

6.2.1 Emergence of magnetic video tape recording: Quadruplex technology for broadcasters

Television recording was identified as a potential application by the electronics industry in the 1920s and 1930s when television broadcasting emerged and television sets entered a steadily increasing number of homes. Without proper recording capabilities, television had to be 'live' all the time, which was troublesome for television producers as well as presenters, performers and actors. Different approaches had been tried to record television images, including "groove and needle" solutions analogous to phonographic disc recording in the music industry, and "intermediate film" solutions which used motion picture film.[1] The first approach had not resulted in workable solutions, while the second approach had become the dominant form of television recording. It was not without its drawbacks, since it was laborious and required chemical processing which prevented instant replay. National television broadcasters in the United States could employ time-zone delay only with highly trained and stress resilient personnel who needed to develop the film as quickly as possible to deliver the recorded programme from the East coast to the West coast within several hours.[2] As the television industry grew rapidly after the Second World War,[3] the need for a more flexible recording technology became pressing. It became a "reverse salient" for the further growth of the television broadcasting system.

During the war, the American electronics industry had profited from contract research for the military. When the war ended, they began looking for new, non-military markets. A recent innovation in the field of audio recording was identified as a promising point of departure within the electronics industry. A magnetic audio tape recorder had been developed in Germany in the 1930s and had been improved by the Germans during the Second World War. The so-called *Magnetophone* used plastic tape with magnetic coating.[4] It was an enormous improvement to existing magnetic *wire* recording approaches which had been around much longer. During the war, Americans had noticed the German's superior recording technology and, when the war was ended, Army engineers brought the *Magnetophone* to the United States. German patent rights were nullified and captured technical documents were made available to the American industry. In 1946, the *Magnetophone* was demonstrated to the radio engineering community in a meeting of the Institute of Radio Engineers (IRE) by an Army engineer.[5] The use of magnetised tape, rather than wire, was acknowledged by the radio engineering community to be a breakthrough in magnetic recording technology. Several American companies began working on a magnetic tape

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[1] See Abramson (1955) for a short history of television recording.

[2] Lovell (1953) gives a telling account of the highly standardised but nerve-wracking procedures.

[3] In 1952 there were 108 television stations and 34.2 percent of the American households owned a television set. Four years later, the number of television stations had increased to 516, and the percentage of television set owner to 71.8 percent (Zielinski, 1986: 75).

[4] AEG-Telefunken and IG Farben (later BASF) were among the pioneers of magnetic tape recording. The *Magnetophone* had been a commercial success and was used in military communications, intelligence applications, as well as radio broadcasting. According to Clark (1999: 9) "[t]he German state radio was the largest customer, using Magnetophones for recording and reproducing programming so that it could be censored."

[5] The Army engineer was Jack Mullin, who later became involved in marketing the recording device in the United States (Zielinski, 1986: 69).

recorder, including Bing Crosby Enterprises,[6] Magnecord, Minnesota Mining and Manufacture Company (3M), and Ampex,[7] taking the *Magnetophone* as an exemplary model. In Europe, Telefunken, the BBC and others, also became active in research and development in the field of magnetic tape recording. The radio broadcasting industry was quick to adopt the new recording technology, as it not only had superior sound quality, but also featured instant replay, erasability and reusability of recordings. In Japan, the American occupation force introduced magnetic tape recording to electronics companies like Toshiba and the start-up Sony (Aspray, 1994). These companies succeeded in designing and producing tape recorders within a few years. By the early 1950s, several companies had familiarised themselves with magnetic audio recording, and the operational principles were known to every major player in the field through publications, product demonstrations, exchanges of knowledge, and reverse engineering efforts. The magnetic audio tape recorder became a collectively shared exemplary model which formed the point of departure for efforts to develop a magnetic video tape recorder.

From an engineering perspective, magnetic recording of video signals is not fundamentally different from recording audio signals. The crucial difference is that the amount of information to be recorded per second is much larger. Thus, it was a major technical challenge to find a practicable way to deal with the enormous tape speeds which were required to achieve a sufficiently high information density. Also heads and tapes required substantial improvements to enable "high density" recording. Anticipating that there must be a market for video recording in the steadily growing television broadcasting industry, several companies started out to upgrade audio tape recording to video tape recording in the early 1950s. Among them was RCA which was one of the major players in the American electronics industry. In 1951, in a speech to RCA researchers, RCA's president David Sarnoff had explicitly asked for a high-speed video tape recorder, called the *Videograph*: "Will you please let me have this *Videograph* before 1956?" (Zielinski, 1986: 76). In December 1953 RCA announced in the *RCA Newsletter* that tape recording could be used for video recording. RCA foresaw "great possibilities first for television broadcasting and later, for national defence, for the motion picture and theater industry, for industry in general, for education and for home entertainment."[8] It was a signal for other companies (and the broadcasting industry) that video recording technology could be

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[6] Bing Crosby was a famous performer who had become tired of performing live for radio. Existing sound recordings could not match the quality of live performances. Crosby Enterprises hired Jack Mullin, the Army engineer who had brought the *Magnetophone* to the U.S. to improve the recorder.

[7] Ampex had been founded in 1944 by Alexander M. Poniatoff. It was a small electronics company which been involved in war-related research and development. In order to develop a magnetic audio tape recorder itself, Ampex hired Harold Lindsey, an engineer who had been present at the IRE meeting in which the *Magnetophone* had been demonstrated.

[8] *RCA Newsletter*, nr. 52, 2 December 1953. Quoted in Blom (2002).

expected to be feasible within several years.[9] Thus, there was a clear demand for video tape recording, and there was a common point of departure (i.e. audio tape recording) for the electronics industry. In the first half of the 1950s, several companies would develop their own solutions in an attempt to be the first to introduce a video recorder.

Audio tape recording used a longitudinal scanning method with one fixed head. To record video signals with a similar configuration, the tape had to be pulled with very high speed across one or more recording heads. This so-called "brute force" approach was tried by several companies, including Bing Crosby Enterprises (BCE), RCA, BBC, and Ampex.[10] At the annual convention of the Institute of Radio Engineers (IRE) of March 1954 in New York, engineers from both RCA and BCE presented technical papers on their longitudinal-scan video recorder projects. Neither system employed any unusual signal processing technique (Jorgensen, 1999).[11]

High tape usage was an inherent problem of high-speed recorders. Not only was it impractical, but also costly since tapes were expensive. In addition, heads and tapes were wearing fast with high tape speeds. One known approach to solve this problem was to use rotating heads. Three scanning methods were developed in the 1950s. Ampex developed an "arcuate scan" method in which three heads were mounted on a rotating disc in a perpendicular fashion. The rotating heads made arcuate tracks on the passing tape. Video tape had to be considerably wider than audio tape. Ampex soon abandoned this method for a more promising approach based on "transversal scanning". In this method, four heads were mounted on the edge of a rotating disc which was placed perpendicularly to the passing tape. The heads made straight, but slightly tilted tracks on the passing 2 inch tape. The principle of transversal scanning was already in the public knowledge domain as it had been patented by Marzocci in 1941 for sound recording.[12] This approach required sophisticated electronic circuitry and advanced mechanics because each television frame was recorded with four heads. Moreover, in the early 1950s, it was very difficult to produce video heads which were exactly the same. A third method was called "helical scanning". In 1960, when Toshiba would surprise the American electronics industry with the first working prototype of a helical scan recorder, it would claim to have begun

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[9] Within Philips this publication was used as an input in strategic discussions (Blom, 2002).

[10] Ampex had licensed magnetic video recorder technology from the Armour Research Institute (later: Illinois Institute of Technology).

[11] Arrangement of BCE: ½-inch tape on 14-inch reels, running at 100 in./s; 10 tracks of multiplexed video, each with a bandwidth of 0.39 MHz; 1 track for the video sync; 1 track for FM audio.
Arrangement of RCA: ½-inch tape on 17-inch reels, running at 360 in./s; 1 track for video luminance signal plus sync; 3 tracks for the video color signals: red, green, and blue; 1 track for FM audio.
Arrangement of BBC: ½-inch tape on 20-inch spool, 200 in./s; 2 tracks of video (bandsplit) plus sync: dc to 100 kHz (FM), 0.1-3 MHz (AM); 1 track for FM audio (Jorgensen, 1999).

[12] U.S. Patent, 2,245,286 "Electromagnetic sound recording".

working on this in 1953 (Sawasaki *et al.*, 1960). In this approach one or more heads were placed on a rotating drum around which the tape was wrapped in such a way that the head(s) would make relatively long slant tracks on the tape.[13]

Rotating heads required sophisticated circuitry and high-precision mechanical engineering.[14] Large parts of the circuitry and most of the components had counterparts in audio recording systems, radio and television. Engineers working on magnetic video tape recording could draw upon shared knowledge reservoirs of recording, radio and television engineering knowledge, complemented with their own expertise in the field of television, radio, and/or recording. "The complication [arose] mainly because the video/audio system [had] to combine, in one instrument, the functions of a whole group of different circuits normally used for different purposes, and get them working together in one harmonious whole." (Olivier, 1971: 19). In 1956, the project leader of Ampex remarked that it had been known for several years "to those intimately connected with or interested in the extensions of the field of magnetic recording into much wider band applications that there [were] three promising approaches toward the development of a tape recorder for television use." (Ginsburg, 1957: 178). Drawing from a shared knowledge reservoir, engineering teams chose different approaches and were incommunicative about their advances until patent positions had been secured and a prototype could be demonstrated.[15] In the "electronics underground" of the Bay area, where among others Ampex was located, rumours and stories circulated (Rosenbloom and Freeze, 1985).[16] A good patent position was important in the electronics industry because it allowed companies to enter into cross-licensing negotiations — a practice used by leading electronics firms to protect and divide markets. Leading electronics companies as RCA depended to no small extent upon licensing revenues. Patents were also important to appropriate rents from investments in research and development. Much of the knowledge embodied in video recorders could be reverse engineered by engineers in rivalling companies as soon as they could get their hands on it. This was possible because electrical engineers shared the same (background) knowledge and were able to interpret configurations. On the level of components, however, such reverse engineering was much more difficult. (Cf. the previous case studies on the "impenetrable" materials technologies reinforced concrete and paint).

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[13] The helical scan method also became known as the slant track method.

[14] Later, the discipline of "mechatronics" would emerge which combined electronics and high-precision mechanics.

[15] This strategy is illustrated by a remark made by one of the early protagonists of video recording at a conference: "We aren't going to say anything about it until we have finished it." (Anonymous, 1957: 188).

[16] Rosenbloom and Freeze (1985: 121) recount how a young engineer (Maxey) heard about Ampex's project in 1954 through the "electronics underground" of the Bay area and managed to see the project leader Ginsburg and convince him that he should join the team.

Once patent positions were secured and prototypes had been developed, demonstrations were given to show progress and get commitments from top management, complementary producers, suppliers and potential customers. Investing in R&D is inherently risky, and management and engineers tried to reduce these uncertainties by keeping an eye on what others were doing. The riskiness was increased by the fact that actors anticipated that there would be significant first mover advantages. Thus, on a collective level a "race" dynamic emerged in which several variants competed to be the first. Demonstrations gave companies an opportunity to take stock of their rivals' technological advances and intentions. Ampex, for instance, witnessed a (restricted) product demonstration by RCA in 1954 which was intended to demonstrate RCA's progress and to affirm its pioneering reputation. Impressed by RCA's advances, Ampex engineers feared that RCA had beaten them, and considered stopping their own VTR project (and allocate their resources differently). When Ampex assessed that RCA's machine had serious shortcomings, it continued working on its own transversal scan VTR (Zielinski, 1986).

As it turned out Ampex was the first to demonstrate a convincing prototype to the broadcasting industry. In 1956, the VTR project team had given a satisfactory internal demonstration of its prototype to Ampex engineers and managers. This was quickly followed by a demonstration to engineering executives of the major television networks CBS, ABC, CBC, and the BBC, who had been requested not to disclose or discuss what they had witnessed with anyone before Ampex had given its first public demonstration at the 1956 convention of National Association of Radio and Television Broadcasters (NARTB, later NAB). This demonstration before NAB members was a great success and immediately Ampex received many orders. The fact that the machine was still in a prototype stage did not scare off broadcasters, which indicates the pressing need for new recording technology in the television broadcasting industry. To satisfy eager demands from broadcasters, Ampex quickly built sixteen VRX-1000 production prototypes, which were supplied to NBC,[17] ABC, and others. The experiences gained in production and operation were used to develop and produce the final product VR-1000 in 1957. Operation of the large and complex machines, or "monsters" as they were called by broadcasting engineers, required skilled operators. It was particularly difficult to achieve interchangeability of recordings. The slightest difference in head sets could make playback impossible. Uniformity of heads, therefore, was of vitally important. In collaboration with operators, Ampex learnt much about television recording and operational requirements. As experiences accumulated, Ampex and its suppliers succeeded in producing robust configurations while incorporating (additional) requirements from broadcasters in the design.

With Ampex's technological lead and patent position secured, Ampex engineers began to disclose parts of their knowledge base. At the convention of

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[17] At the time, NBC was part of RCA which was a major competitor of Ampex.

the Society of Motion Picture and Television Engineers (SMPTE) in 1956, Ampex engineers presented their recording technology and described in detail the various problems they had encountered in the development of the VTR and the steps they had taken toward solutions. These presentations were subsequently published in the *Journal of the SMPTE* (Ginsburg, 1957; Anderson, 1957; and Dolby, 1957). Not before long, everybody in the field of video recording was informed about Ampex's approach to video tape recording, and the Ampex engineers gained a reputation for themselves as they became well-known figures in the field. Other electronics companies tried to get their hands on an Ampex machine in order to reverse engineer the VTR and approached broadcasters who had bought an Ampex machine. RCA had ties with NBC, while Japanese companies were offered a chance to study the recorder after the Japan National Broadcasting Corporation (NHK) had imported its first Ampex VTR in 1958. NHK invited engineers from Sony, Toshiba, Matsushita, JVC and other Japanese firms to examine the Ampex recorder. The Japanese Ministry of International Trade and Industry (MITI) wanted to limit imports of the $50,000 Ampex machine as it preferred a domestic version being developed. It organised a VTR research group, subsidised replication efforts by firms, and NHK engineers provide these firms with valuable technical data. In only three months, Sony, in cooperation with NHK's central laboratory, succeeded in replicating the four-head Ampex VTR. JVC's engineers familiarised themselves with the Ampex technology by copying NHK's VTR for in-house study in 1958-1959 (Rosenbloom and Cusumano, 1987). Thus, within a relatively short time, VTR technology was shared within the international electronic industry. It became a collective base for further developments in video recording technology.

By being the first, Ampex succeeded in creating a virtual monopoly in the American television broadcasting market, and at the end of the 1950s, Ampex's VR-1000 configuration had become the dominant design. Characteristic of this design was a transversal scanning method using four heads. Therefore, the VTR was named *Quadruplex*. The tape was 2 inch wide, enabling almost perpendicular tracks. Interchangeability of recordings between machines was a major user requirement, therefore the chances of other incompatible formats were reduced considerably once a significant number of broadcasters had adopted *Quadruplex*. As an increasing number of broadcasters adopted the Ampex VR-1000, it became increasingly mandatory for other broadcasters to also adopt the Ampex machine if they wanted to exchange recordings. While interchangeability between machines made by different manufacturers was impossible, even interchangeability of recordings made with different VR-1000s, was not obvious because it was very difficult to make uniform heads and tapes.[18] The slightest

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[18] In a panel session during the SMPTE Convention of 1968, it was recalled that in "1957, 1958, 1959 — despite the fact that there were only two sources of machines, (…) there weren't any two successive machines that would interchange with each other." (Anonymous, 1968: 744).

deviations made playback on other machines impossible.[19] Ampex with its suppliers put in many efforts to uniformise and standardise their configurations to assure interoperability. High precision production methods were required with very small margins of tolerance. While heads were manufactured by manufacturers of VTRs themselves, tapes were produced by a complementary producer. In the mid-1950s, 3M was the only commercial source for video magnetic tape in the United States. "Consequently, the problems of uniformity of performance [were] relatively few. As more manufacturers enter[ed] the field, however, it [became] necessary to develop standards in regard to tape oxide characteristics in addition to the dimensional standards for tape and reels (…)." (Benson, 1960).

While *IG Farben* had been the first to introduce a plastic tape with magnetic coating in the 1930s, the first magnetic tape development programme in the United States had been initiated by Brush in 1943 as a part of a contract with the federal Office of Scientific Research and Development. In collaboration with Batelle Memorial Institute, which had expertise in materials science and chemistry, many experiments were performed with different coatings, also using paint pigments as particles. After experiments had yielded promising results, Brush attempted to interest Eastman Kodak, Meade Paper, 3M, and Shellmar, which were experienced in large-scale coating techniques. Initially, only Shellmar showed interest. After the war, when German *Magnetophone* technology was made available, 3M became interested in magnetic tape and went on to establish a magnetic tape development laboratory. Also Audio Devices, Indiana Steel Products, and Armour Research became active in tape development. In 1947, 3M introduced the first commercial paper-based tape, which was followed one year later by a magnetic tape with a cellulose acetate base. As the market for magnetic tapes grew, more manufacturers became active in the field of magnetic tape. Spurred by demands for high-performance tape for video tape recording, as well as increased competition, technological advances and improvements were made (Grooch, 1999).

In 1957 Ampex made a cross-licensing agreement with RCA which gave Ampex a license of RCA's patents on colour television in exchange for licenses on the Quadruplex VTR. Ampex and RCA effectively split the market, two-thirds for Ampex and one-third for RCA (Graham, 1986). Managers of both companies agreed that their engineers could freely exchange technical (though

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[19] In 1960 CBS engineer Benson (1960) remarked that "[o]riginally, because of the uniformity of head manufacture did not assure acceptable playback on heads other than the one used for recording, it was necessary to hold the recording head assembly in storage with the tape until the time of air playback." By 1960, however, "complete interchangeability of head assemblies exists, providing the necessary stringent precautions regarding manufacture and adjustment are observed. As a result, techniques which are common in the motion-picture business have been adopted for many of the more involved television productions."

not manufacturing) know-how for some months. In this way, also knowledge on transversal scan recording which was not been disclosed could be acquired by RCA. In Europe, Ampex licensed major electronics companies like Philips. Ampex was too small to set up an effective European organisation itself. Moreover, adaptations of the VR-1000 were required because different television standards were used in Europe.[20] Ampex chose Toshiba to create a joint venture in an attempt to get access to the restricted Japanese market. Ampex engineers helped Toshiba engineers with knowledge on the *Quadruplex*. Meanwhile, Toshiba kept working on a helical-scan VTR. Ampex refused to grant patent rights to several other Japanese companies, which induced efforts to "invent around" Ampex's patents. JVC, for instance began to work on another approach to video recording "that would bypass the key Ampex patents." (Rosenbloom and Cusumano, 1987: 8). Thus, even if companies did not get a license to use Ampex's proprietary technology, patented solutions shaped their approach to video recording, if only to invent around patents. This agonistic form of knowledge sharing induced the generation of new ways to create similar performances, resulting in the creation of a reservoir of technological options.

While Toshiba began manufacturing Quadruplex VTRs, it kept working at a helical-scan VTR. Sony and JVC knew about Toshiba's achievements in helical scanning, because there were personal ties between the technical leaders of the three companies, which dated back to school days (Rosenbloom and Cusumano, 1987). Western manufacturers, however, were taken by surprise when Toshiba demonstrated a working prototype at the SMPTE convention of 1960. The helical scan VTR used only one revolving head and was capable of recording a whole television field on a slant (diagonal) track on a standard width (2 inch) tape. Toshiba emphasised the relative simplicity of its configuration in comparison with the *Quadruplex* which used four head and required a much more complex circuitry (Sawazaki *et al.*, 1960).[21] Moreover, it was argued that mutual interchangeability was better than that achieved with the conventional system. On the broadcasters market, however, the Toshiba machine was too late to be successful since *Quadruplex* already had locked in television broadcasters. That different companies continued to put in efforts in video recording

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[20] In America and Japan the NTSC standard was used, whereas in Europe two television standards (PAL and SECAM) were in use.

[21] According to Toshiba, the advantages of their helical scan VTR were: "(1) Operation and adjustment difficulties can be avoided. No special technique is necessary for handling. In general, the new system does not have such problems as "venetian blind," skewing, and scalloping. (2) The apparatus is simplified. The one-head system uses one amplifier whereas the conventional video-tape recorder uses four. The electric switching devices are thus rendered unnecessary. (3) Dropouts are greatly decreased. Experimental results have shown that dropouts are but a small fraction of those with the conventional system. (4) At recording mode, the picture recorded on the tape can be monitored simultaneously by the monitor head. (5) The new system can reproduce the picture at any tape speed, whether fast forward, slow forward, rewinding, or stopped. This greatly facilitates the effective montage or splicing of tape." (Sawazaki *et al.*, 1960).

technology was because new markets for video recording were envisioned (see next section).

The first *Quadruplex* VTR (VR-1000) was far from perfect, and Ampex and RCA continued to make incremental improvements upon its original design, while at the same time extending their knowledge bases on video recording. Major design goals were to make the machine more versatile, easier to operate, smaller, and more reliable. In the manufacture of VTRs and their components, unprecedented precision engineering was required. Increasingly, Ampex with its suppliers succeeded in making their machines more robust. In the early 1960s, several improvements and extensions of video recording were introduced by Ampex and RCA, which included Selective Electronic Editing (enabling inserts and assemblages), Time Element Compensation (enhancing interchangeability of tapes), Automatic Time Control, Colortec (enabling phase correction for colour recordings), InterSync (enabling smooth inserting), and InterSwitch (enabling interchange of images made according to different international television standards). The basic design of the *Quadruplex* was left basically unaltered.

Innovative developments on the level of components altered the interdependencies in the actor constellation. The introduction of the transistor made it possible to improve the design of the *Quadruplex* considerably. In the 1950s, Sony had become a leading firm in transistor technology, and Ampex made a cross-licensing agreement with Sony to profit from its know-how on transistors in exchange for licenses and support on video recording. Between 1959 and 1961 there were "many visits of engineering teams from Redwood City [Ampex] to Tokyo [Sony] and vice versa. Ampex's main interest was access to Sony's knowledge and experience in producing solid state electronics. The negotiations apparently fell through over patent and intellectual property disputes." (Mallinson, 1999: 160). The first transistorised *Quadruplexes* were introduced in the early 1960s by Ampex and RCA. VTRs could be made smaller, lighter, and more robust. This allowed VTRs to be mounted on vehicles, enhancing the functionality of video recorders by enabling television makers to record programmes on location. It would take until 1968 before Ampex introduced a portable *Quadruplex* which weighted only 16 kg.

The creation of a collective reservoir of knowledge about the *Quadruplex* VTR was supported by standardisation activities which were triggered by interoperability requirements. Almost immediately after the introduction of the *Quadruplex*, several broadcasters had started *ad hoc* standardisation groups to establish recommended operation practices, and to provide Ampex and RCA with specifications to enable interchangeability. These standardisation efforts were taken over by the professional society SMPTE which set up a committee for standardisation of video tape recording in response to "the pressing need for standardisation in this field" (Kolb, 1958). The committee included experts from both users (the major networks CBS, ABC, NBC, and an independent station) and manufacturers (Ampex, RCA, and 3M), as well as experts from the broadcaster's association NAB, and the professional society SMPTE. The two major VTR manufacturers in the United States, Ampex and RCA, having secured their markets, allowed their employees to contribute to SMPTE's standardisation initiative. Members of the committee participated on a personal basis and were expected to act in the best interests of the field.

In 1958, SMPTE's Video-Tape Recording Committee met for the first time. It drew up a list of items requiring industry standardisation in order to assure interchangeability of recorded video tapes. The list included tape dimensions, tape reels, tape track dimensions; audio, control and cue track standards; monochrome and colour signal characteristics; tape leaders; standard tapes; and tape splicing (Lind, 1959).[22] The committee functioned as a clearinghouse for standards and recommended practices, and provided the industries of both producers and customers with rules and guidelines. Since the *Quadruplex* was the only viable technological option (because of the "lock-in" of the market), committee standardisation was relatively unproblematic. With SMPTE in an intermediary role, the *Quadruplex* approach to video recording was institutionalised. The *ex post* standardisation process was mostly a matter of establishing which factors influenced interchangeability, and on making agreements on these factors. As a result, *Quadruplex* VTRs became a fully standardised piece of equipment for television broadcasters which allowed for interchangeability of recordings made on different machines.

By the early 1960s, video recording technology (as a new step in magnetic tape recording technology) had become part of a collective knowledge reservoir. The operational principles were widely shared, as a result of demonstrations, publication, knowledge exchanges in alliances, reverse engineering activities, and standardisation processes. Manufacturing know how, on the other hand, was only shared in joint ventures. The developments in video recording occurred in a context which was pre-structured by outcomes of earlier cosmopolitanisation processes. From the outset, there was a collective knowledge reservoir with codified knowledge on television and magnetic recording technology. There was an elaborate infrastructure for interaction and exchange between electrical engineers. IRE, SMPTE and NAB, for instance, were part of this infrastructure. Electrical engineering was professionalised, and as professionals electrical engineers valued exchange with other engineers — while taking into account that appropriability was important as well.

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[22] In 1960, a survey of interchangeability factors resulted in the following list: (1) video head: quadrature alignment, gap azimuth alignment, vacuum guide position, and recorded track dimensions; (2) control track: control signal phasing, edit pulse phasing, recorded signal levels, track width and placement; (3) video signal: carrier frequency for blanking level, carrier frequency for white level, pre-emphasis, post-emphasis, video bandwidth; (4) audio head and track:: track width and placement, gap azimuth alignment; (5) audio signal: recorded signal level, pre-emphasis, post-emphasis, audio bandwidth; and (6) magnetic tape: physical dimensions and properties, magnetic properties, reel dimensions. "[T]he majority of the factors are subject to set-up or operating adjustment and must be held under careful control if interchangeable performance is to be comparable to that achieved in noninterchangeable operation." (Benson, 1960).

Technological affordances for production of translocal knowledge were created by a relatively high level of complexity, which called inter-firm alignments and alliances (e.g. Ampex who needed RCA's knowledge on colour television, and Sony's knowledge on transistors). Interchangeability requirements created affordances for standardisation which involved knowledge production. The actor constellation was characterised by a few innovative companies, large professional customers, suppliers of magnetic tape, and collective actors like IRE and SMPTE. A limited number of electronics companies in the United States, Japan and Europe, were engaged in R&D activities and kept an eye on each others advances. The dominance of broadcasters induced standardisation. Once broadcasters had selected the *Quadruplex* it became the dominant design for the professional market. During an "era of incremental change" it became better understood how the performance could be made robust.

While *Quadruplex* had locked-in television broadcasters, the demonstration of the helical-scan VTR by Toshiba, had clearly demonstrated that different approaches to video recording were feasible. Other companies, including Ampex, were also active in developing this alternative configuration. The helical-scan approach was to become the basis for a range of new product-market combinations.

6.2.2 New horizons for video recording technology

While standardised *Quadruplex* recording technology dominated the broadcasting market, new approaches to video recording were tried to develop video tape recorders for the institutional (audio-visual) and consumer markets. *Quadruplex* technology was generally considered to be too complex and expensive to be used for these markets. Reductions in number of heads, tape width, and complexity of circuitry and mechanics (mechatronics) became leading design criteria within the field of video tape recording technology. Size, weight, tape usage and price had to be reduced considerably to appeal to institutional users like schools, training centres, and, *a fortiori*, to consumers. Within Philips, for instance, a list of requirements was drawn up which lead to the conclusion that in some respects demands on a VTR for non-professional use were greater "than those imposed on the more expensive studio equipment." (De Lange, 1965: 178).[23]

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[23] Philips' list of requirement included eight items (De Lange, 1965 178):

1. Since it has to be operated by non-technical people, the apparatus should require no critical adjustments, and there should be no risk of damage by errors in operation.
2. It should be possible to connect the recorder to a normal television set without the latter having to be radically modified. This applies both to recording and playing back a programme. The recorder must also be able to work in a closed-circuit television system, i.e. in combination with a television camera, a microphone and a video monitor.
3. The apparatus must be easily transportable.
4. Tape consumption should be such that the tapes are not too expensive or too bulky.
5. A reasonable playing time without interruption should be possible.

Speculations about an eventual mass market for video recorders dated back to the mid-1950s. Consumer electronics companies anticipated that the market for (colour) television sets would get saturated by the end of the 1960s, and they needed a follow-up product for the highly profitable television set. A VTR for home-use was considered a good candidate (Graham, 1986).[24] The anticipation that VTRs could become a consumer product was widely shared. But how this could be achieved was far from obvious. With regard to the form of the technical configuration, a longitudinal scanning (or "brute force") approach, despite its inherent drawbacks connected with high tape speed, was chosen by a number of companies as a (renewed) point of departure in their open-ended search processes. Others preferred a helical scan approach, which could work with one or two heads — rather than the four which were required in *Quadruplex* configurations. With regard to the function of the VTR, different options were identified by marketeers and industry observers. First, home users could use a VTR as convenience recording of television programmes ("time shift"). Second, VTRs could be used for home viewing of purchased or rented movies, using the television set as a monitor. Third, in combination with consumer cameras, they could also be used for home movie production. If the second option was preferred by most consumers, then video tape recording might not be the best design option. In analogy with music records, other magnetic and non-magnetic approaches, using a disc, seemed more promising — especially for companies which had not built up a good patent position in magnetic tape recording, such as RCA. A "groove-and-needle" approach was an example of an altogether different approach to video recording.

Thus, companies in the electronics industry faced uncertainty as to what approach to follow. Investments in R&D would be considerable, and failure would be costly. As an input in strategic decision making, America's leading consumer electronics company RCA performed an extensive survey and made a classification of all existing approaches to video recording and playback in the early 1960s. RCA considered movie purchase the most likely application for consumers. Home movie production was thought to remain limited to the oc-

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6. No particular high demand should be made on the constancy of the voltage or frequency of the supply mains.
7. The picture quality need not be equivalent to that obtained with professional recorders, but should still be acceptable.
8. The price must be substantially lower than that of professional video recorders.

[24] Within RCA, for instance, strategists had predicted that the market for colour television would decrease from 1970. "For the RCA Laboratories this meant that the company would need an "act to follow" that was both as big as television, and as broad in scope. The only way for the Laboratories to be recognized as the continuing major source of RCA's long-range opportunities was for this crucial new product to be closely identified with it." (Graham, 1986: 85). "The videorecorder concept had a classic RCA systems appeal. As a possible consumer product, it had been around the RCA Laboratories in some form since the early 1950s. Thought of as a synthesis of television and recording, both entertainment areas in which RCA had a substantial business and research stake, the project was comprehensive enough technologically to provide an opportunity for different groups in the Laboratories to work together toward a common goal." (90).

casional videophile. It was concluded that video tape recording — whether longitudinal or helical scan — might not be the best way to reach consumers. Video tape recording was considered to be a "spent technology" within the RCA technical community, and there would be little room for necessary improvements and reductions in size, weight, tape usage, and price (Graham, 1986). Candidates with more potential as a consumer product were various disc-based devices.[25] Nevertheless, RCA kept working on a consumer VTR in parallel with working on disc-based videoplayers. Other companies were less sceptical about the feasibility of a consumer VTR.

As leading companies in the market of magnetic video tape recording, Ampex and RCA undertook research in longitudinal scan VTRs, if only for defensive reasons and to increase their absorptive capacity. Within RCA, for example, "reports were circulating that other companies, Sony among them, were developing magnetic videorecorders for eventual use in the consumer market." (Graham, 1986: 94). Other companies were more enthusiastic about the opportunities of the "brute force" or "fixed head" machines. The first demonstration of a working longitudinal scan configuration specifically aimed at the consumer market was given in 1963 by a British company named Telcan. It was a relatively simple and low-cost VTR which used ¼ inch tape — which was eight times narrower than the standard 2 inch tape used in *Quadruplexes*. While some industry observers disqualified it as a hoax, it did trigger a VTR project at Fairchild Camera and Instruments' Winston group (Jorgensen, 1999). One year later, Fairchild/Winston announced a ¼ inch VTR which incorporated improvements to transports, heads, and tapes. Meanwhile, efforts to create a longitudinal recorder went on elsewhere as well. In 1965 Wesgrove Electronics demonstrated its ¼ inch prototype. Ampex announced a ¼ inch longitudinal scan VTR in the same year. In 1967 Newell announced a unique high-speed VTR that only had three moving parts. In the mid-1960s there were various attempts to configure a VTR for home use with one of more fixed heads.[26] None of the attempts was successful, however. As it turned out, the inherent problems of high tape usage, limited recording time, and head abrasion remained problematic. As a result, resources for this line of research and development dried up, and longitudinal scanning approaches disappeared before a convincing VTR could be demonstrated. Ampex, for example, decided to withdraw from longitudinal scanning and focus instead on helical scanning which by then had emerged as a more promising approach to video recording.

In 1960, Toshiba had been the first to show a prototype of a helical scan VTR (for the broadcasters market). Ampex and RCA had also been working on helical scan video tape recording technology, but had not yet progressed suffi-

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[25] RCA distinguished three possible approaches: an electromechanical, an optical, and a capacitance approach (Graham, 1986).

[26] For an overview of developments in longitudinal scanning VTRs see Jorgensen (1999).

ciently to be able to demonstrate a properly working prototype. Rosenbloom and Freeze (1985) recount how Ampex had heard rumours that RCA and perhaps some Japanese companies were about to demonstrate models using helical scanners. Ampex expected that the NAB convention of 1960 would be used as a forum. In secret, Ampex took two prototypes to the NAB convention, to be shown only if other companies did likewise. "The "NAB machines" — one color, one monochrome — were not really ready to be shown; nor was Ampex ready to meet the expectations such a demonstration would have generated among its customers." (Rosenbloom and Freeze, 1985: 137-9). Ampex was relieved that the rumours appeared to be false, only to be unpleasantly surprised at the SMPTE convention two months later, when Toshiba got the limelight. The anecdote illustrates how companies were jockeying for position and used demonstrations to do so. It also shows the tension between the desire to keep one's develops secret and the need to be seen as a pioneering company.

Toshiba's demonstration clearly showed that helical scanning was promising from an engineering perspective, if only because fewer heads and less complicated circuitry were needed to get an acceptable picture quality. In the first half of the 1960s, Toshiba's demonstration was followed by a range of announcements and demonstrations of helical scan VTRs by companies from Japan (JVC, Sony, and Matsushita), Europe (Philips,[27] Loewe Opta, and Grundig) and the United States (Machtronics, Ampex, Precision Instruments, Dage Television, Westel, Arvin Industries, and AVCO). In 1965, Sony was the first manufacturer to introduce a helical scan VTR aimed specifically at the mass market.[28] Sony's CV model of 1966 was important because it enabled Sony "to apply for a number of very crucial patents as a result of that development." (Aspray, 1994).[29] This gave Sony a good position in cross-licensing negotiations.

Although all of the VTRs shared the same underlying principle of helical scanning, the variation was enormous.[30] Each manufacturer developed its own format which defined the electrical, mechanical, and magnetic characteristics of the recordings. None of the machines was successful on the institutional, let alone the consumer, market. Without exception they were too expensive, too large, and/or too complicated to use. Nevertheless, all these attempts contrib-

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[27] In the early 1960s, Philips had not built up a strong patent position in magnetic video tape recording, and depended to a large extent on Ampex's and RCA's patents. For magnetic tapes, Philips depended on companies like BASF, AGFA, Scotch and 3M (Sander Blom, 2002).

[28] In 1965, Sony introduced the TCV-2000 and TCV-2110 on the consumer market, which were ½ inch, helical scan VTRs in black and white, and cost around $1,200. In 1966 Sony introduced the CV-2000, a ½ inch VTR, both black and white and colour, which could record 60 minutes and cost around $800.

[29] Interview with Sony engineer Kihara in 1994 as part of IEEE oral history project. He added: "Those patents have survived. They govern the basics of video tape recording and are still held in connection with Betamax and the 8mm development as well. There's a good comparison also with the CD there, where there were a number of patents that came out of that development as well." (Aspray, 1994).

[30] There were variations in number of heads (one or two), tape width (varying from ½ inch to 2 inch), track width, angle of track, wrap angle (α- or Ω-wrap), tape speed, rotation speed, loading method, etc.

uted to a continually growing collective knowledge repertoire on helical scanning VTRs in the 1960s. Various contributions were made to increase recording density and efficiency. In 1965, for example, Sony was the first to introduce a "field-skip method" in its small ½ inch CV-2000 model. With this method, tapes could be used much more efficiently. It took a rival like Philips two years develop its own field skip technology (Blom, 2002). In 1968, Matsushita introduced an "azimuth recording" method in its model NV-2320. This method also reduced tape consumption considerably. In the 1970s, all video tape recorders would incorporate these methods.

Another important advance was the introduction of the video cassette, an idea which would be adopted by every manufacturer in the field. In the mid-1960s, Philips had succeeded in making its *compact audio cassette* a worldwide standard.[31] The introduction of the cassette had contributed enormously to the use of audio tape recorders in homes and cars. Audio cassettes made audio tape recorders a genuine, easy-to-handle consumer product. With cassettes, users no longer had to thread tapes by hand. This clearly was an idea to be imitated in the field of video recording. Since VTRs used much more complicated threading methods than audio tape recorders — because of wrapping around rotating heads — new, more complicated, cassettes and loading mechanisms had to be developed. Different companies developed various (two-reel) cassettes or (one-reel) cartridges. In 1969, Sony was the first to demonstrate a video cassette recorder (VCR) prototype. Philips and others were quick to follow with their own (incompatible) prototypes.

At the end of the 1960s, Sony, JVC, Matsushita, Philips and others, all had converged on a basic design of using helical scanning with two heads and tapes encased in cassettes or cartridges. "In 1970, engineers at the leading firms within the electronics industry "had access to all the technologies required to design a VCR for the mass market. The remaining tasks were to synthesize the various design elements and to create a manufacturing facility capable of low-cost volume production." (Rosenbloom and Cusumano, 1987: 11). Manufacturers learnt from each other by visiting demonstrations and conferences, by exchanging information and knowledge, by reading each other's publications, by studying patents, and by reverse engineering each other's VTRs.

Alliances were important in the way knowledge became shared. Ampex, for instance, had formed a joint venture with Toshiba (Toamco), while Philips and Matsushita had formed a joint venture (Matsushita Electronics Corporation) in 1952. Such joint ventures gave Western companies a means to get a stake in the Japanese market in exchange for technological knowledge. Even Sony, which was known to follow an independent strategy, sought collaborations and was interested in establishing good relations with the international leading electrical firms, including Philips (Blom, 2002). In 1966 Philips and Sony

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[31] Companies like CBS, RCA and 3M also had developed different cassettes, but Philips succeeded in creating the world standard by giving away licenses of its cassette format for free.

made an agreement to exchange technological information and knowledge in the field of video recording. The agreement provided for collaboration in design and development of video recorders for the mass market in anticipation of standardisation. Both companies agreed not to contest each other's patents (Blom, 2002).

Since none of the VTRs had sufficient commercial success, no *de facto* industry standard emerged in the 1960s. As a result, there were many different formats on the market, which put off potential customers who did not want to take the risk to buy an incompatible format which would not become the industry standard. The huge variety also prevented any company to achieve economies of scale which could have brought the price down. The American professional society SMPTE had set up a standardisation subcommittee for helical scan recording in 1964 to establish standards which would enable interchangeability — notwithstanding the Committee's assessment one year before, that it was

> "…believed probable that it will be difficult if not impossible to obtain concurrence on any one form or type of helical record due to the diverse nature of current developments. It is probable that any attempt at standardization in this field at this time would be premature and that enough time must elapse to permit the advantageous features to emerge before taking action that might inhibit development." (Morris, 1963).

Electronics companies were reluctant to participate in standardisation work as long as it had not been established which format would become dominant, and as long as they saw a chance to define the industry standard themselves, whether or not through alliances. While broadcasters had been able to pressure the industry into standardisation (also by eager adoption of a format which was not yet perfected, thereby precluding introduction of other formats in their market), consumers were unable to exert such pressure and preferred to wait. The VTR Standardisation Committee of the SMPTE could not do much more than to keep track of all the formats that were announced or introduced in the market. These overviews demonstrated the enormous variety of formats. The Subcommittee for helical scan recording, which had been set up as a forum to enable collective action towards standardisation and the establishment of best practice recommendations, could do little more than make up a list of items which affected interchangeability of tape recordings (Remley, 1970). To its regret, the SMPTE Committee had to conclude in 1968, that manufacturers "just will not agree" and that apparently, manufacturers had "agreed on only one thing, and that is to disagree." The committee could do little more than "publishing pro and con articles in the *Journal [of the SMPTE]* (…) to help to get the waters a little clearer and a little quieter." (Anonymous, 1968).[32] Notwith-

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[32] When asked about is progress in standardisation of helical scan recording, the Committee answered: "Unfortunately, we haven't done anything. We have had a committee active and we have had three meetings. We have tabulated something like 26 different slant-track recording formats, plus some and

standing its failure to create standards, the Committee formed a forum for interaction between manufacturers.

To understand why manufacturers did not (want to) reach an agreement on a standard format for helical scan recording, anticipations on market dynamics have to taken into account. For the consumer market, interchangeability was likely to be a very important requirement, especially if video recorders were to be used for home viewing of movies, whether purchased or rented. For content providers and retail traders, if was important to have only one or a few formats, otherwise their costs would increase considerably. Users wanted to be sure that the format of their choice would be catered for by content providers. Thus, interchangeability created network externalities, which would give the first manufacturer which succeeded in creating sufficient mass, a significant advantage.

At the same time, however, it was difficult to achieve sufficient mass since users and content providers were hesitant to buy into a format prematurely. Many preferred to wait and see which format would become dominant. This created a chicken-and-egg problem. Therefore, both alliances between manufacturers, and alliances between manufacturers and content providers, were important to create such mass. While antitrust regulations made it difficult for American manufacturers to make agreements, such collaborations were actively encouraged in Japan by MITI. MITI had identified video recording as a strategically important technology for Japan and promoted standardisation to give the Japanese electronics industry a competitive advantage in the international market. In 1968 the Electronics Industry Association of Japan (EIAJ) succeeded in getting Japanese companies to agree on a standard format for ½ inch, helical-scan, one head, open-reel video tape recorders for semi-professional users. Where SMPTE had failed to achieve *ex ante* standards, MITI and EIAJ succeeded in pressuring manufacturers into standardisation. Within SMPTE, the Japanese EIAJ standard was welcomed as a "sign of progress", and work was undertaken "to draft an American National Standard to duplicate the EIAJ Type I format." (Remley, 1970).

MITI also stimulated collaboration between Japanese companies in the field of consumer video cassette recorders (VCRs). Notwithstanding fierce competition, Japanese companies had a tradition of maintaining an informal network in which they exchanged information on each other's research on new products (Ketteringham and Nayak, 1987). Sony was a relative newcomer in the Japanese industrial landscape and was somewhat of an outsider. This was aggravated by its opportunistic and aggressive attitude. However, Sony had become a leading company in the field of video tape recording in the second half of the 1960s. It had obtained several important patents which gave Sony a strong

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minus some — they come and they go. I am able to report this progress: that there is a general decline in the number of new formats. However, we have had no agreements in the committee other than to hold to half-inch, one-inch, and two-inch tape, and to utilize NAB hubs and the NAB recording characteristics for audio." (Anonymous, 1968).

position in the industry. As it increasingly succeeded in creating a genuine consumer VCR which was not too large, too expensive, nor too complicated to use, Sony began trying to get other manufacturers in Japan behind its *U-Matic* format. A joint approach would be profitable for all participating parties, because it would create credibility and sufficient mass in the global consumer market. In 1970, Sony persuaded seven other Japanese manufacturers, including Matsushita and JVC — all of which had previously announced their own video cassette recorders, but were not as far as Sony — to the adopt Sony's format. Part of the agreement on the U-Matic format was that the participants would give each other free access to all technical improvements that any one of them would achieve. The U-Matic collaboration, therefore, contributed to the creation of a collective repertoire on video cassette recording in Japan. Every major manufacturer in Japan became knowledgeable about Sony's state-of-the-art technology.

The U-Matic was not as successful on the consumer market as anticipated, and after one year the collaboration was terminated. The U-Matic, however, did well in the institutional (audio-visual) market which created sufficient revenues for Sony to keep investing in further research and development aimed at reducing size and cost. Management of JVC was disappointed and cancelled research and development on video tape recording in favour of a video disc approach which by then had become a serious — although far from completed — alternative for tape-based recorders. As success of a VCR failed to materialise, a videodisc player was increasingly considered a good alternative for the videotape recorder. In analogy with the music industry, record players were mass-produced artefacts, while audiotape recorders were only owned by audiophiles. The same could become true for videodisc players and videotape recorders. This added uncertainties to a continued support for R&D in videotape recording.[33] In secret, however, researcher at JVC continued a bootleg project on video recording. Outside of Japan, RCA and Philips were among the companies which continued to put in efforts to be the first to succeed with a consumer VCR.

The U-Matic alliance in Japan had caused worries within RCA. It had made RCA reconsider if it still made sense to invest in video tape recording technology in which it did not have a strong patent position anyway, or whether it should focus on a video disc approach in which it was making progress. RCA began to gather intelligence on their rivals' activities. Technical experts moni-

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[33] A major difference with videotape recorders was that commercial success of videodisc players strongly relied on the availability of software (e.g. Hollywood movies), and commitments from content providers were considered vitally important. Content providers, like Hollywood studios, were reluctant to distribute their films on disc, fearing that it might harm their core business, i.e. distribution through cinemas. There was a large variety in approaches to videodisc players: RCA worked on three approaches simultaneously, using capacitance, holography and laser; Philips worked on a laser-based system called *Video Long Play*; Matsushita working on a mechanical "groove and needle" *Visc* system; and JVC worked on a capacitance-based system (Graham, 1986).

tored developments in the industry and attended competitor's demonstrations in Europe and Japan. These visits, especially the visit to a demonstration of Philips' *VCR*, resulted in modifications to RCA's own *Magtape* system (Graham, 1986). With hardware improvements leading to lower manufacturing costs, RCA hoped that it could beat its Japanese rivals. The very exacting design and manufacturing tolerances required to produce interoperable VCRs, made lower manufacturing costs an important factor. RCA failed to get support from other American companies to adopt its format as a standard. In 1972, RCA signed up only two manufacturers to produce its VCR. Two years later, RCA had to acknowledge that it had not succeeded in achieving "the necessary performance level at the required level of cost to allow the Magtape system to be a profitable venture for the company." (Graham, 1986: 148). By then, the number of companies with a stake in the ongoing VCR standardisation battle was reduced to Sony, JVC, Matsushita, and Philips. Ampex had withdrawn from the race, and chose to focus on the professional market in which it still had a strong position.

While there were many uncertainties about which system would eventually become successful on the consumer market, much of the technological knowledge and skills needed to design a VCR for home-use were shared by engineers at the leading consumer electronics companies, such as RCA, Sony, Matsushita, JVC and Philips. A large amount of literature and handbooks had been published on video recording, "written by experts for experts." (Oliver, 1971: 11). Also books for non-experts were published, explaining the principles of video recording and classifying the various approaches and formats.

Table 6.1 illustrates the enormous variety of VTRs and VCRs in the 1960s and (early) 1970s. I will not describe the various variants in detail; it suffices to note that this variety was possible because of a shared repertoire of video recording knowledge.

Table 6.1. Overview of VTR/VCR developments 1961-1976 (adapted from Zielinski (1986)).

Year Model	Manufacturer	Country	Product-level	Characteristics	Application (intended)
1962					
VTR-1	Toshiba	Japan	Market introduction	2 inch, helical-scan, VTR, colour (NTSC) Variant: 1 inch	Broadcast Institutional
JVC-770	JVC	Japan	Market introduction	2 inch, helical-scan, colour (NTSC)	Broadcast
SV-201	Sony	Japan	Prototype	2 inch, helical-scan, colour (NTSC); ca. $ 10,000	Broadcast
MVR-10/11	Machtronics	USA	Prototype	1 inch, helical-scan, VTR, b&w, mobile (41 kg), MVR-11: $ 13,850	Institutional
Optacord 500	Loewe Opta	BRD	Market introduction	1 inch, helical-scan, VTR, b&w, max. 100 minutes	Institutional
VR-1100	Ampex	USA	Market introduction	2 inch, transversal-scan, Quadruplex, transistorised, compact	Broadcast
TR-11	RCA	USA	Prototype	2 inch, transversal-scan, Quadruplex, colour, transistorised	Broadcast
Colortec & Electr. Edit.	Ampex	USA	Market introduction	Peripherals for colour accommodation and electronic editing	Broadcast
EL 3400	Philips	NL	Experimental model	1 inch, helical-scan, VTR, b&w, max. 60 minutes	Institutional

1963					
TR-22	RCA	USA	Market introduction	2 inch, transversal-scan, Quadruplex, transistorised, colour, for multiple TV standards	Broadcast
VR-8000	Ampex	USA	Prototype	2 inch, helical-scan, VTR, compact, 59 kg	Institutional
VR-660B	Ampex	USA	Prototype	1 inch, helical-scan, VTR, compact, under 50 kg	Institutional
PI-3V	Precision Instr.	USA	Prototype	1 inch, helical-scan,, portable (31 kg), $ 12,150	Institutional
-	Telcan Ltd. Cinerama	GB / USA	Experimental model	¼ inch, longitudinal-scan, VTR, extremely compact, b&w, ca. $ 200 (in mass production)	Mass market
KV-2000	JVC	Japan	Market introduction	1 inch, helical-scan,, VTR, compact, colour (NTSC)	Institutional
1964					
DV-2000	Dage Television	USA	Market introduction	1 inch, helical-scan, VTR, ca. 67 kg, $ 12,450	Institutional
VR-2000	Ampex	USA	Market introduction	2 inch, transversal-scan, Quadruplex, High Band, for Europe, over $ 60,000	Broadcast
EL-3400	Philips	NL	Market introduction	1 inch, helical-scan, VTR, max. 45 kg, 45 minutes, $ 3,950	Institutional
EV-100	Sony	Japan	Announcement	½ inch, helical-scan, 1.5 heads, $ 3,000	Mass market
CV-200	Sony	Japan	Prototype	½ inch, helical-scan, VTR, skipfield, compact, $500	Mass market
VE-5001	Fairchild / Winston	USA	Announcement	¼ inch, longitudinal-scan, VTR, ca. 90 kg $3,000 - $4000, also models under $500	Institutional; Mass market
BV-120	Sony	Japan	Market introduction	2 inch, helical-scan, VTR, ca. 90 kg, $14,400	Broadcast
1965					
-	Wesgrove Electrics	GB	Prototype	¼ inch, longitudinal-scan, VTR, b&w, $395 - $792	Mass market
BK-100	Grundig	BRD	Prototype	½ inch, helical-scan, VTR, b&w, 90 minutes	Mass market
PI-7100	Precision Instruments	USA	Prototype	1 inch, helical-scan, VTR, colour (NTSC)	Institutional
Optacord 600	Loewe Opta	BRD	Prototype	1 inch, helical-scan, VTR, ca. 18 kg, ca. $2,500	Institutional
VR-7000	Ampex	USA	Market introduction	1 inch, helical-scan, VTR, colour (NTSC)	Institutional
HVR-6200	Ampex	USA	Announcement	¼ inch, longitudinal-scan, VTR, 50 minutes	Mass market
TCV-2000 & TCV-2110	Sony	Japan	Market introduction	½ inch, helical-scan, VTR, b&w, $1,200	Mass market
1966					
VR-303	Ampex	USA	Market introduction	¼ inch, longitudinal-scan, VTR, 50 minutes, $3,950	Mass market
WRC-150	Westel Corp.	USA	Prototype	1 inch, helical-scan, VTR, portable, 10.4 kg	Broadcast & Institutional
CV-2000	Sony	Japan	Market introduction	½ inch, helical-scan, VTR, 60 minutes, b&w and colour, $800	Mass market
1967					
-	Newell Assoc.	USA	Prototype	¼ inch, longitudinal, VTR, recorder for high-speed (mass) copying	For home video
AV-3400	Sony	Japan	Prototype (Market introduction in Japan)	½ inch, helical-scan, VTR, portable, 25 kg (became famous as the first “Sony Porta-Pak”), $1,495	Mass market
KV-600/800 801 & 811	JVC	Japan	Market introduction	1 inch, helical-scan, VTR, colour for NTSC, PAL and SECAM	Institutional; Broadcast

1968					
VR-3000	Ampex	USA	Market introduction	2 inch, transversal-scan, Quadruplex, portable, 16 kg	Broadcast
EVR/-BEVR	CBS	USA	Prototype	Cassette system motion picture film and electronic scanning, EVR for replay only	Mass market; Broadcast
CVR-XXI	Arvin Industries	USA	Prototype	½ inch, helical-scan, cartridge, B&W and colour	Mass market
	Sony, Matsushita/JVC and several other Japanese manufacturers reach an agreement through the EIAJ on the standard EIAJ-I (½ inch, helical-scan, 1 head, open reel) for semi-professional users				
1969					
LDL-1000	Philips	NL	Market introduction	½ inch, helical-scan, VTR, 45 minutes, b&w	Mass market; Institutional
BK-100	Grundig	BRD	Market introduction	see 1965 announcement	Mass market; Institutional
NV-3080 VTR-450T	Panasonic	Japan	Prototype	½ inch, helical-scan, VTR, portable	Mass market
VCR	Sony	Japan	Prototype	1 inch, helical-scan (VCR = Video Cassette Recorder), colour (NTSC)	Broadcast; Institutional
U-Matic	Sony	Japan	Prototype	¾ inch, helical-scan, VCR, colour, $350 – 750, 80 minutes, stereo sound	Mass market
SV-707 U	Shibaden / Apeco	Japan	Prototype	½ inch, helical-scan, open reel, portable	Mass market
1970					
VCR …	Philips	NL	Several prototypes	½ inch, helical-scan, cassette, colour, 60 minutes	Mass market; Institutional
VT-100	Akai / Videovision	Japan	Market introduction	¼ inch, helical-scan, b&w, portable, 4.6 kg	Mass market
Instavision	Toshiba + Ampex = Toamco	Japan USA	Prototype	½ inch, helical-scan, cartridge, colour, 7.5 kg, max. 30 minutes, $800 (b&w)- $1,000 (colour)	Mass market; Institutional
Cartrivision	Cartridge TV / AVCO	USA	Prototype	½ inch, helical-scan, cartridge, colour, 120 minutes, $895, mainly for prerecorded cartridges	Mass market
KV-350 PV-4500	JVC	Japan	Market introduction	½ inch, … EIAJ-I, stationary / portable	Mass market
VR-7003 PAL	Ampex	USA	Market introduction	1 inch, helical-scan, VTR, portable, 46 kg	Institutional
1971					
U-Matic	Sony, JVC, and 10 other manufacturers	Japan	Market introduction	¾ inch, helical-scan, cassette, 60 minutes, colour, standardisation through EIAJ	Mass market; Institutional
VCR-1205	Philips	NL	Prototype	½ inch, helical-scan, cassette, b&w, 60 minutes	Mass market
LT-3150	Bosch	BRD	Market introduction	½ inch, helical-scan, VTR	Institutional
VCRN-1500	Philips	NL	Prototype	as VCR-standard with colour	Mass market
BK-210+300	Grundig	BRD	Prototypes	½ inch, helical-scan, VCR-standard	Institutional
BK-2000	Grundig	BRD	Prototype	½ inch, VCR-standard with colour	Mass market
1972					
EV-1500 A/E	Hitachi	Japan	Prototype	Cartridge player for NTSC and PAL	Institutional
BCR	Bosch / Philips	BRD / NL	Prototype	1 inch, helical-scan, High-Band, colour	Broadcast
PVR-709	Audiotronics	USA	Market introduction	½ inch, EIAJ-standard, colour	Institutional

BK-204 / Color	Grundig	BRD	Market introduction	1 inch, helical-scan, open reel, stereo, 110 minutes	Institutional
BK-401 / Color	Grundig	BRD	Market introduction	as BK-204 with electr. editing	Institutional
1973					
	24 manufacturers reach an agreement to adopt Philips VCR standard				Mass market; Institutional
1974					
LVR	BASF	BRD	Announcement	½ inch, longitudinal, cassette	Mass market
1975					
BCN-20	Bosch / Philips	BRD / NL	Market introduction	1 inch, helical-scan, portable, 18 kg	Broadcast
HR-3300	Matsushita	Japan	Prototype	½ inch, helical-scan, cassette, colour, 120 minutes (VHS – Video Home System)	Mass market
SL-7300	Sony	Japan	Market introduction in USA and Japan	½ inch, helical-scan, cassette, colour, 60 minutes (Beta), $1,300	Mass market
BK-2500	Grundig	BRD	Market introduction	Colour VCR standard	Mass market
VCR N-1501	Philips	NL	Market introduction	Less expensive VCR-standard	Mass market
1976					
HR-3300	Matsushita / JVC	Japan	Market introduction in USA and Japan	VHS-cassette recorder	Mass market
BK-3000	Grundig	BRD	Prototype	VCR-standard, 2nd generation	Mass market

In Europe, Philips demonstrated ½ inch VCR prototypes in 1970 and 1971, and introduced its VCR N-1500 on the European market in 1972. It was one of the first consumer VCRs in terms of price and performance. Philips' VCR configuration became influential, as its VCR arrangement with built-in tuner, time-switch, and rf-remodulator was imitated by other manufacturers and became a standard formula for consumer VCRs (Jackson, 1980). Within the consumer electronics field it was anticipated that the American market would be decisive in creating a worldwide standard. Anxious to exploit its technological lead, Sony began looking for support for its format in America. Worried that Sony would gain a decisive lead, Philips refused to back Sony's format, and made a countermove in which it tried to find support for its own VCR format in the United States. However, the main target for support in the United States, RCA, did not want to commit itself to one format at that point, while other American manufacturers wanted exclusivity — which for Philips was unacceptable in its attempt to set the standard (Blom, 2002). In Europe, Philips had more success as it succeeded in 1973 in reaching agreements with 24 manufacturers to adopt its format. By then, the European consumer electronics industry as a whole became increasingly worried about Japanese dominance, and preferred not to help the Japanese consumer electronics industry in setting a world standard.

Meanwhile, Sony continued making the ¾ inch U-Matic more suitable for the consumer market, thereby focusing on cassette size reduction — rather than playing time extension. In 1974 a ½ inch prototype "Betamax" VCR could be demonstrated. Again, Sony tried to get other manufacturers behind its format. Having identified the American market at the crucial battle field in standardisation, Sony showed its Betamax prototype, which could record up to one hour, to RCA hoping that RCA would adopt it. RCA, however, chose to wait for formats to emerge with a longer playing time before making any commitments. In its own marketing research RCA had concluded that recording time should be sufficient to record a football match, i.e. circa three hours. Turned down by RCA, Sony started negotiations with Matsushita and a few other Japanese companies (Perry, 1988). Sony's technological lead and its sunk investments made the space for manoeuvring small, and no agreements on "joint development" were made (Cusumano *et al.*, 1997). Without the backing of the other major players, Sony introduced its Betamax format in 1975 on the market in Japan and the U.S.

Meanwhile, JVC (revitalising its bootleg VCR-project) and Matsushita went on to develop their own formats, VHS and VX respectively, which were partly based on licenses of Sony and on knowledge gained while collaborating on Sony's U-Matic. They concentrated on a longer recording time, rather than cassette size reduction. In 1975, just after Sony had introduced its Betamax in the market, JVC told its parent company Matsushita about its VHS format. In 1976, after Betamax had been revised to play two hours, Sony retried to form alliances in order to set the standard. In the effort, Sony, JVC and Matsushita showed each other their Betamax, VHS, and VX machines, but again they did not reach agreement over a common standard. Matsushita held a key position in negotiations, because it had built up a large manufacturing capacity. Its decision to adopt one or the other format could be decisive in the ongoing standardisation battle. Subsequently, Sony demonstrated its machine to Hitachi, Sharp, Mitsubishi, Toshiba and Sanyo, and also asked the MITI to support the Betamax format. MITI's intervention was to no avail — only Toshiba and Sanyo decided to back Sony, but other firms, including JVC's parent company Matsushita, decided to wait for the VHS format which JVC had announced in 1976 (Cusumano *et al.*, 1997). JVC began marketing its VHS in 1976, and Matsushita adopted it in 1977 as its standard for the consumer market. "Matsushita was known for competing in that manner: monitoring a broad range of technical developments and gradually building up in-house skills while waiting for Sony, JVC, or other innovative consumer-electronic firms to introduce a new product." (Cusumano *et al.*, 1997: 80). Looking back, after VHS had beaten Betamax in the 1980s, JVC's willingness "to let other companies participate in refining the standard, such as moving from two hours to longer recording times or adding new features" was an important factor in JVC's success to create alliances (ibidem, 84).[34] "Allowing partners to share in development also improved the

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[34] In addition, "Sony's leaders believed that the Beta design was good enough to be a winner, and they knew they were ahead of their rivals in VCR development. (…) Sony set out to interest other VCR

VHS in ways that JVC might not have pursued itself." (84). Moreover, JVC also provided considerable assistance in manufacturing and marketing. Since manufacturing VCRs required very high precision, licensees needed such manufacturing know-how — which indicates that replicating a VCR in a laboratory is one thing, but mass-manufacture quite another.

While Sony and JVC/Matsushita were engaged in a standardisation battle in the United States, Philips still had hopes it would be able to set the standard for Europe. Philips did not have a strong position in the United States, because in cross-licensing agreements with American electronics companies it had been agreed not to be active in each other's home markets. Acknowledging that Philips' format could not win in the American market, the American branch of Philips, North America Philips Corporation, was inclined to adopt Sony's Betamax format after it had been introduced in 1975. At the same time, Matsushita with whom Philips had formed a lucrative joint venture in the 1950s, preferred Philips to adopt the VHS format. If Philips would choose Betamax for the American market, it would endanger its joint venture with Matsushita in Japan. In 1977, Philips reached an overall understanding with Matsushita, in which it was agreed that Philips would maintain its own format in Europe, while its American branch would adopt the VHS format (Blom, 2002; Cusumano *et al.*, 1997)

Meanwhile, the different television standards (NTSC vs. PAL/SECAM) ceased to be technological barriers behind which Philips could take refuge when Japanese companies succeeded in manufacturing PAL versions of VHS recorders. Matsushita offered Philips to collaborate to make VHS a standard in Europe, in anticipation of making VHS a world standard. Philips declined as it wanted to capitalise on its own format. Most European electronics companies, still favoured Philips' format because the Japanese consumer electronics industry was perceived as a major threat for the European industry as a whole. In 1979, however, sales of Philips N-1500 and the recently introduced N-1700 dropped. In order to beat Japanese competition, a new VCR was developed. In an ultimate effort to surpass both VHS and Betamax, Philips developed a new format:V2000. Although V2000 probably was a better design than VHS and Betamax, Philips had fallen behind in production capacity. Japanese manufacturers could profit from economies of scale, which gave them a vital competitive advantage vis-à-vis Philips. In the American consumer electronics industry, V2000 was too late to create much enthusiasm, since every manufacturer had already committed itself to either Betamax or VHS. At the same time, Sony and Matsushita became increasingly active in European markets which were identi-

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pioneers in adopting the Beta format., concentrating especially on winning the allegiance of Matsushita, its most formidable rival." But Sony did not want to delay commercialisation of the Betamax in order to cooperate, and probably compromise, on the development of an industry standard with other firms, and Sony was reluctant to build VCRs for its licensees. It was an innovative producer under its own brand name, not an Original Equipment Manufacturer (Cusumano *et al.*, 1997: 82).

fied as growth markets. Philips succeeded in gaining time when it filed a complaint of dumping practices to the European Committee in the early 1980s. Philips action was backed by several other European electronics companies, including Grundig, Siemens and ITT (Blom, 2002). MITI and the European Committee made a Voluntary Export Restraint agreement, which gave Philips some breathing space. Realising that it could not win the standardisation battle, Philips decided to start assembling VHS recorders, based on technological expertise accumulated during the development of the V2000. Since JVC's and Matsushita's VHS recorders incorporated patents owned by Sony, and Sony had been unwilling to license Philips, Philips had been forced to invent around Sony's patents, which had been made possible thanks to its V2000 project. Philips succeeded in manufacturing VCR according VHS format within months.

In the mid-1980s, the VHS format emerged as a winner in a standardisation battle. Cusumano *et al.* (1997: 81) conclude that "[s]trategic manoeuvring by the principal protagonists in 1975-77 led to an alignment of producers of the core product and to the exploitation of mass production and distribution capabilities sufficient to account for the early dominance of VHS sales. In a second phase of rivalry, in the 1980s, the strategic alignment of producers of complementary products [e.g. prerecorded tapes] reinforced the VHS advantage and hastened the demise of Beta[max], which might otherwise have survived as a second format."

Although the standardisation battle often gets the limelight in studies on video recording, for cosmopolitanisation of magnetic video tape recording it is only the end-phase of a twenty-year long process in which technological knowledge was generated by various actors, and in which rivals built on each others advances. During the 1950s, 1960s and 1970s, numerous knowledge exchanges, demonstrations, announcements, publications, and alliances, shaped the terrain in which the later battle for an industry standard was fought out.[35] The three remaining formats (Betamax, VHS, and V2000) all were based on the same knowledge repertoire.

The development of the VCR was a process which lasted more than two decades. Dertouzos *et al.* (1989: 54) rightly conclude that competitive success in industries in which products and production processes are technologically complex, "is rarely the result of overnight breakthroughs; rather it is built on years

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[35] Examples of presentations are the presentation of the Betamax VCR by Sony engineers in 1976 in a forum of the IEEE (Kihara *et al.*, 1976). JVC and Matsushita engineers presented their VHS VCRs two years later within the IEEE (Shiraishi *et al.*, 1978; Sugaya, 1978). Like his colleagues at JVC and Matsushita, Kihara from Sony was a member of the IEEE. He published several books on VTR for educational and professional engineering purposes in Japan. He also gave lectures and published papers in the Journal of SMPTE, Journal of the ITEJ (Institute of Television Engineers of Japan), Technical Review of EBU (European Broadcasters Union), and Electronics.

of effort, years spent testing, adjusting, improving, refining, and in the process accumulating detailed technical knowledge of products and production techniques." It should be added that knowledge exchanges and the forming of technological alliances were also important parts in the dynamics. In other words, it was not just internal knowledge production in industrial labs, but also the circulation between labs which was important in the built-up of knowledge reservoirs on video tape recording.

With the benefit of hindsight, it can be concluded that first mover advantages for Sony were limited. Cusumano *et al.* (1997: 76-7; emphasis added) conclude that "[w]ith technologies and markets that require years to develop, being the inventor or first mover in commercialization may not be as useful as coming into the market second or third, *as long as the rapid followers have comparable technical abilities*, which usually result from having been among the pioneers who participated in developing the technology for commercial applications. (…) Follower pioneers and later entrants may also exploit investments made by the first mover, such as in solving engineering and manufacturing problems (*if the solutions become public knowledge*) or in educating buyers in the use of a new product (…)."

It is clear that cosmopolitanisation was shaped by anticipations and business strategies aimed at exploiting first mover advantages, but the dynamics were largely the result of increasing interweaving of actors and unintended outcomes of multi-actor processes. The VHS videocassette recorder that eventually became the standard for home-use, was the result of many efforts by many contributors. In the two decades years from 1956 until the mid-1970s, no single firm dominated the technological developments, and most firms were quick to assimilate technologies developed by competitors.

6.3 In conclusion

The pattern of cosmopolitanisation in the case of magnetic video tape recording differs from cases of reinforced concrete and paint. Knowledge was produced on multiple levels: on the level of components, on the level of the subassemblies, and on the level of the VTR/VCR product architecture. Knowledge on the level of the product architecture, about which components had to be incorporated and what functions they should fulfil, became widely shared by pioneering companies in the electronics industry in an early stage. Knowledge on lower levels, however, was not part of this collective reservoir. Competition was largely about knowledge on these lower levels and about mass-production know-how. In other words, the "dominant design" was anticipated before market selection, and the main struggle was about how this anticipated design could be filled in.[36]

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[36] This is an addition to dominant design literature, which focuses on battles between rivalling designs.

The concept of video tape recording emerged in a context which was shaped by outcomes of earlier cosmopolitanisation processes within the field of electrical engineering. The main knowledge producers were professional engineers who worked in industrial research laboratories and were members of professional societies with their forums and esprit de corps. Thus, knowledge production in the case of video recording was shot through with pre-existing cosmopolitan elements. The emergence of a cosmopolitan technology was anticipated from the start. Video recording technology was not an isolated technology: it was at the cross-roads of developments in television technology, magnetic (audio) recording technology, and electronic circuitry. From the outset, there was a collectively shared knowledge of audio tape recording which provided a collective point of departure for research in video tape recording. The development of the VTR was a response to a clear demand from the television broadcasting industry for a more flexible recording technology. The magnetic audio tape recorder had already been a technological and commercial success in the radio broadcasting industry. Anticipating on the television recording market, several companies commenced research and development work in their labs to develop a high-density recorder. Combining different bodies of knowledge, different project teams of engineers tried to be the first to develop a working prototype. Thus, the industrial lab mode of knowledge production was present from the outset. Knowledge production was interwoven with business strategies: anticipations on first mover advantages created the dynamics of a race between different variants. In contrast with the previous two case studies, there was no "local phase" in cosmopolitanisation. From the start, there was a race in which rivals kept a close eye on each others' advances, and in which informal exchanges occurred — i.e. an "inter-local" phase characterised by competition.

While outcomes of earlier cosmopolitanisation processes created affordances, there were also specific technological characteristics which created additional affordances. In particular, the interoperability requirement was important because this meant that VTRs (within one "format") had to be compatible and be able to play recordings made with another machine. In the early stages, this was not easy given the complexity of the artefact and the high-precision engineering which was required. On the level of components, heads and tapes required many R&D efforts to enable the manufacture of uniform components which could be treated as a blackbox on the level of the artefact. VTR producers needed to know exactly how the performance was achieved, and which variables influenced interchangeability. Only after market introduction the "monster" (as broadcasting engineers called the first VTR) was tamed with the help of feedbacks from broadcasting engineers who analysed which variables influenced the performance. It was anticipated that interchangeability requirements would create path dependencies (and a lock-in), because broadcasters would prefer to stick to one format. This raised the stakes for manufacturers, and induced them to keep an eye on competitors, and consider collaboration to reduce risks. Such strategic behaviour was further stimulated by the fact that artefacts like a VTR could be reverse engineered by rivals once they could get their hands on it. Appropriation strategies, therefore, aimed at exploiting a head start (locking-in customers) and patenting (to gain a strong position in cross-licensing negotiations), rather than at trying to keep knowledge a trade secret as was the case in the case studies of reinforced concrete and paint.

The actor constellation consisted of innovative electronics companies as main knowledge producers, components suppliers (in particular tape manufacturers with their own competition), and professional customers. During the inter-local phase the situation was fluid, and rivalry between VTR producers was high. Producers remained secretive until patent positions had been secured and a working prototype could be demonstrated. Prototypes were demonstrated to create alignments with top management, suppliers, complementary producers, and (potential) customers. It was used to signal progress while it provided rivals with an opportunity to assess advances and decide whether continuation of their research efforts was worthwhile. Broadcasters were dominant customers, and were interested in robustness and reliability of performance, thus creating an affordance for cosmopolitanisation.

A "trans-local" phase began after Ampex was the first to demonstrate a convincing prototype and broadcasters decided to purchase VTRs, although it was still in a developmental stage. Having lost the race, RCA made a cross-licensing agreement with Ampex in which engineers of both companies exchanged know-how. Broadcasting engineers initiated *ad hoc* standardisation activities in an attempt to understand how the performance could be made robust. These standardisation activities were later taken over by the SMPTE, and experts from Ampex and RCA were happy to participate since it contributed to a further institutionalisation of their technology. The trans-local phase was characterised by committee standardisation and further (incremental) improvements of the *Quadruplex* VTR. The *Quadruplex* became a standardised dominant design. Knowledge about the product architecture was widely shared within the industry through presentations, strategic alliances, joint ventures, standards, recommended practices and reverse engineering efforts. Broadcasting engineers played an important part in the circulation and aggregation of experiences. In Japan, both the national broadcaster NHK as well as MITI played important roles in stimulating firms to reverse engineer the *Quadruplex* — in which they succeeded in a relatively short time. In the 1960s, while being incrementally improved, the *Quadruplex* became a standardised and cosmopolitan technology. It was taken up in standards, recommended practices, handbooks, textbooks, articles in technical journals, etc., and it became part of a collective repertoire of video tape recording. Until the 1970s, the *Quadruplex* remained the only viable alternative for broadcasters — also because (backward) compatibility was important as broadcasters did not want their archives with recording to be incompatible with new generations of VTRs.

Technological developments in video recording did not end there. In parallel with cosmopolitanisation of the *Quadruplex*, alternative VTRs were developed for other markets. Every owner of a television set was identified as a potential buyer of a VTR. Especially the introduction of the transistor, which enabled miniaturisation, reinforced anticipations that a consumer VTR should be possible. Within the consumer electronics industry, a miniaturised VTR was identified as a very promising consumer product. A new race dynamic emerged, as manufacturers started to develop their own solutions for a consumer VTR which was possible because of a shared repertoire. Several variants dropped out of the race, and eventually only a few contenders remained which all incorporated the similar helical scan arrangement. Although much of the basic knowledge of magnetic video recording was shared by pioneering companies, it remained difficult to actually create a configuration which could meet all the requirements in terms of size, weight, price, ease of operation, etc. As it turned out, R&D efforts required large investments and a long-term commitment while success was not guaranteed. During this extended research effort new and improved prototypes built on predecessors. Again, it was important to show progress to create and maintain alignments, even though convincing prototypes could not (yet) be demonstrated. Advances by one company were imitated by others. This time, there were no customers who would purchase a technology which was not yet completed or who would pressure manufacturers into *ex ante* standardisation. Instead, many consumers waited to see which format would win. This created a threshold. In the early 1970s some contenders withdrew altogether from the race. Companies tried to create alliances in order to increase the chance of success. This signalled the beginning of a trans-local phase of knowledge production, in which companies increasingly sought collaboration with other firms in anticipation of standardisation. Interoperability requirements in combination with an anticipated mass-market created affordances to share knowledge and create sufficient mass to profit from first mover advantages. There were (shifting) technology alliances between pioneering companies (e.g. Sony and Philips), thus creating a process of agonistic knowledge sharing. There were also commercial alliances between pioneering companies and OEMs (original equipment manufacturers) in which knowledge was transferred. In Japan, MITI stimulated collaboration between Japanese firms which resulted in a temporary U-Matic collaboration in which Sony, Matsushita and JVC exchanged knowledge. The U-Matic became the basis for the eventual Betamax and VHS formats. In Europe, Philips succeeded in creating alignments with most of the European manufacturers as part of a collective effort to compete with Japanese companies. Eventually, JVC and Matsushita were most successful in creating alignments and achieving sufficient mass to profit from network externalities. In the 1980s VHS became the *de facto* standard, and other firms, including Philips, began manufacturing VHS VCRs. The VHS format became a mandatory format for users as well as producers and content providers. In this final phase a *de facto* cosmopolitanisation occurred: when VHS became a dominant design, knowledge about the VHS product architecture became dominant as well.

In conclusion, the affordances created by outcomes of earlier cosmopolitanisation process were influential. Pre-existing regimes and infrastructures played an important part in the case of video tape recording. Also the historical setting in the 1950s was important, because by that time industrial research had been institutionalised in the electronics industry. Cosmopolitanisation of knowledge was anticipated from the start. It makes a difference whether a technical community emerges and co-evolves with a new technology, or whether the basic elements are already present. In this case, there was an electrical engineering community with an esprit de corps, and members who valued reputational rewards — as is indicated by their presentations in conventions and conferences and participations in committees. This pre-existing infrastructure also allowed for informal knowledge exchange between teams of engineers from different companies. Since they shared a common cognitive background, they could appreciate each others contributions and enabled them to reverse engineer each others configurations. On the one hand, professional engineers were rivals working for competing companies. On the other hand they were members of the same community and valued reputational rewards.[37]

Typical for R&D-dependent innovation patterns, knowledge was largely produced in industrial laboratory settings. This was a major difference with the previous two case studies in which knowledge producers initially relied on experiential knowledge. R&D was aimed at realising the shared promise of video tape recording. The shared promise and the anticipation on first mover advantages and lock-ins created the dynamic of a race in which participants were interdependent and the outcomes were uncertain. Although outcomes were uncertain, there was consolidation of expectations about the artefact's configuration and its function.[38]

In technological alliances knowledge was shared and reproduced. It was a major goal for innovative companies like RCA, Sony, JVC and Philips to incorporate their proprietary knowledge in the eventual industry standard because this would guarantee them revenues from licenses. I.e., the patents which were included in the industry standard determined how the royalties would be carved

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[37] MacDonald (1996) argued that for senior management a problem with engineers is "that they take great delight in solving problems, and the more complex the problem, the greater the delight an engineer normally has in giving away the solution." (220). The reward for "giving away" solutions is reputation with a professional community. It also creates reciprocity as professional comcollegues will be obliged to return the favour. For senior management, the benefits of an enhanced professional reputation and reciprocity obligations are not immediately important. However, MacDonald (1996) also notes that is has been established that senior management does value information acquired by informal means. It can be argued that from the point of view of the organisation (as carried by senior management) appropriability is important, while from the point of view of the professional, exchange takes precedence. In the latter case, appropriability still plays a role, in the way that the success must be attributed to the (individual) professional, and so enhance his status and credibility.
Graham (1986) has described the 'double loyalty' of engineers at RCA.

[38] While Callon (2002) argues that competition between firms to arrive first can only happen within a consolidated actor configuration, this case study shows that consolidation in terms of expectations about nature and function of an artefact (+market) suffices to get this kind of battle.

up. Although SMPTE and other intermediaries offered forums for *ex ante* standardisation, this did not happen and the battle was fought out between different groups of firms. The standardisation battle turned out to be a costly affair for the parties which lost. This was a learning experience and became part of a repertoire of how to deal with such races.[39]

The heterogeneity of the actor constellation was limited: the main knowledge producers were large electronics firms with similar background knowledge. They had sufficient resources to undertake laboratory research, and did not rely on collaborative R&D. Research capabilities were major assets in the competitive dynamics. Whereas producers in the cases of reinforced concrete and paint were unable to undertake such costly and uncertain effort on their own and organised collaborative research efforts, producers in the case of video recording undertook research largely on an individual basis. Only firms with substantial research capabilities (and a strong patent position) were included in cross-licensing agreements. Less innovative firms acted as OEM. Matsushita played an interesting double role: it specialised in mass-production capabilities and became a key actor in the final stages, while investing in research to enhance its absorptive capacity. As a result, the role of intermediary actors in knowledge production at the level of the artefact was limited, although they were important for maintenance of an infrastructure for circulation. Thus, the local-cosmopolitan division of labour was characterised by dominance of engineers working on both levels: within the firm as employees and on the cosmopolitan level as professionals. This might well be typical for cosmopolitanisation in R&D-dependent innovation patterns.

Different types of customers created different affordances. Broadcasters were dominant actors, pressing for, and contributing to, standardisation. Whereas the broadcasters could adopt an unfinished VTR, created an early lock-in, and helped to improve and standardise the VTR, the dynamics in the case of the VCR with a mass-market were different. Consumers adopted a wait-and-see attitude which created thresholds. Network externalities were much higher, because a majority of consumers did not want to buy into a format which would not win the race. Not only did the configuration have to be more robust, it also had to be introduced in sufficient mass which called for alignments with OEMs and content providers. Cusumano *et al.* (1997: 79) rightly argue that "domination of the huge global market required cooperation with other firms in mass production, licensing, and distribution of both hardware

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[39] In the case of the DVD, a successor of the VCR, consumer electronics companies would try to prevent a lengthy standardisation battle and to achieve *ex ante* standardisation to reduce uncertainties and cost inherent in a race dynamic. "It was largely because of memories of [the VCR] war that, in 1995, Sony and Philips reluctantly agreed to pool their ideas for the new DVD with eight other consumer-electronics giants in a group known as "the DVD forum" (*The Economist*, 17-23 June 2002). Although they succeeded in creating a industry-wide consortium, Philips and Sony eventually withdrew when the proposed standard did not incorporate their proprietary technology sufficiently. Again, a standardisation battle emerged, which illustrates that although companies might want to achieve the collective good of standardisation, this will not always work out in this way.

and software." Such cooperations required sharing of knowledge, which relied on the achievement of translocality.

What were technological affordances which shaped cosmopolitanisation? As an assemblage, the video recorder was much less impenetrable than reinforced concrete and paint. Indeed, the basic operational principles were shared by pioneering electronics companies in an early stage. In the case study the role of reverse engineering was highlighted. Knowledge on the level of the product assemblage could not be kept secret. (Mass-)manufacturing knowledge, on the other hand, could not be reverse engineered, and was kept a secret from rivals. For example, as part of cross-licensing agreements, RCA and Ampex engineers exchange knowledge, but not manufacturing know-how.

Interoperability played a prominent role in cosmopolitanisation of video recording knowledge. To produce a VTR which could exchange recordings with another VTR required a thorough understanding of how the performance was achieved. The smallest deviations could result in machines which could not interchange recordings or play prerecorded tapes. While interoperability between *Quadruplex* machines of the same manufacturer already was problematic, the requirement of interoperability between machines made by different manufacturers (e.g. Ampex and RCA) created additional affordances for the production of translocal knowledge.

In the case of the consumer VCR with its anticipated mass market, there were groups of actors working on the same format and within these groups, interoperability had to be achieved. Precision engineering and production knowledge were as important as knowledge on the product architecture. Licensers gave technical assistance to OEMs to help them achieve interoperability. Interoperability requirements also shaped expectations on network externalities and first mover advantages, and induced alignments which content providers — who imposed their own requirements on the design of VCRs.

In sum, as in the cases of reinforced concrete and paint there was a phased pattern of an inter-local, a trans-local, and a cosmopolitan phase. The way translocal knowledge was produced and became part of a collective knowledge reservoir differed. These differences could be understood as an effect of different affordance structures.

Chapter 7
Air traffic control

7.1 Introduction

The case study of air traffic control (ATC) was selected as a case of a complex systemic technology to assess whether my conceptualisation of cosmopolitanisation would also work for technologies in the top of the technological hierarchy. In comparison with materials and artefacts, technological knowledge production on the level of systems is a much more distributed and heterogeneous undertaking, shot through with socio-political processes. To create and maintain ATC configurations that work, management knowledge is likely to be as important as engineering knowledge (Hughes, 1998). Because of the complex nature of ATC systems, knowledge about the design and implementation of ATC systems is likely to be configuration-specific, and it will be difficult to produce translocal knowledge (Davies and Brady, 2000). Thus, it can be expected that cosmopolitanisation of technologies at this level of the technological hierarchy will be different from processes on lower levels.

The goal of ATC is to ensure safe and efficient air traffic. This dual goal hints at an inherent tension in the design and implementation of ATC systems since safety and efficiency can be conflicting. The origins of ATC date back to the 1920s when Rules of the Air were established, and visual navigation aids and radio equipment were implemented to assist pilots in finding their routes. The first ATC centres were established in the 1930s, and after the Second World War, radar technology was introduced at busy airports and in en route control centres. In the 1960s parts of the ATC system were automated, replacing "humanware" (e.g. standardised procedures and ATC language) with hardware and software. Nowadays, satellite systems are increasingly employed. The ATC system has become a highly complex architecture of interconnected systems for communication, navigation and surveillance. The American ATC architecture — by far the largest in the world — consists of interconnected, interoperating, and interdependent sets of systems with are located in approximately 1,800 staffed facilities — airports towers, flight service stations, terminal facilities, en route centres, and a central command centre — and thousands of unstaffed facilities.

To ensure safe and efficient air traffic, interoperability between different elements in the ATC system is a key requirement. In particular, ground-based systems and systems onboard aircraft have to be compatible. Given the international nature of air traffic, systems in different countries have to be interoperable as well. With the tremendous increase in air traffic since the 1950s, performance requirements have become very high. Every time the ATC system became overloaded, its capacity needed to be increased, which became increasingly difficult and costly as the ATC system grew more complex.

The ATC case is an example of a mission-oriented innovation pattern. In most countries, national governments are responsible for design and implementation of ATC systems — also because of national security. In this case study, therefore, the role of "mission actors" and the "common good producers" in the production of technological knowledge will be highlighted (Van de Poel, 1998). The set of knowledge producers is likely to be heterogeneous, and sociopolitical processes are likely to shape the dynamics at this level. Governmental agencies, airspace users (ranging from owners of small aircraft to airlines), research centres, manufacturers of subsystems, societal actors and other (associations of) stakeholders can be expected to try to influence the design and implementation of ATC systems. Safe and efficient air travel is a common good.

To analyse cosmopolitanisation processes, I will focus on knowledge activities at the level of the overall ATC architecture. At this level it is ensured that the overall system will work as an interconnected architecture of interoperable subsystems. Systems integration and systems engineering are important elements in this work. In the case study I will focus on activities and processes that point at systematisation, professionalisation, or standardisation of knowledge production of the architecture level. To get indications of the creation of a collective knowledge reservoir on the design and implementation of ATC architectures, it is important to analyse international activities and interactions, and the role of international forums and intermediary organisations.

The ATC system in the United States is by far the most complex ATC system in the world and will prominently feature in this case study. The United States were the first country where activities on the level of the ATC architecture were systematised — i.e. where an *ad hoc* reactive approach was replaced by a more systematic, coordinated and proactive approach. Developments in Europe will not be neglected, however. In particular interactions between American and European system developers and recent efforts within Europe to harmonise and integrate national ATC systems into an uniform European ATC architecture are relevant.

Characteristic for the development of the ATC system is that it happened in successive "generations". Actors themselves used the notion of generations. For this case study, it is convenient to use the construct of partly overlapping generations.

7.2 Cosmopolitanisation of air traffic control technology

7.2.1 "First and second generation" of ATC

The origins of ATC can be found in the emerging airmail service in the late 1910s and 1920s. At the time, airmail was a lucrative niche, but punctuality and safety were hampered by bad weather and poor visibility conditions. Efforts were therefore undertaken to make all-weather flying and night flying possible. In the United States, the Post Office Department played a central role in establishing navigation aids for pilots. At the end of First World War, it began setting up a system of ground beacons for visual guidance along airmail routes to guide aviators at night and in times of poor visibility. In the 1920s, air travel increased and airlines were established which also made use of navigation aids. The economic importance of aviation for (interstate) commerce was recognised by the federal government, and in 1926 the Air Commerce Act was endorsed by Congress.[1] The Department of Commerce was extended with an Aeronautics Branch which incorporated an Airways Division. As airlines grew in size and number they formed an informal group to mutually coordinate the approach and arrival of their aircraft to prevent collisions. In 1929, the airlines set up Aeronautical Radio Inc. to coordinate the implementation and use of radio equipment onboard aircraft.[2] With a coordinated approach interoperability of equipment on the ground and in the air was realised.

The federal government recognised the (economic) importance of safe air travel, but because of the Depression was unable to invest in the collective goods of navigation aids and communication systems. A consortium of airlines took the initiative to replace visual beacons with radio beacons.[3] As the airways became crowded, the informal system by which airlines exchanged flight data to prevent collisions was identified as insufficient to guarantee safety. Public concerns were raised about safety of air traffic, in particular by people living in the vicinity of busy airports. The Department of Commerce pressed the airlines to develop a more formal system for "en route ATC" with ATC units to ensure separation between aircraft flying in airways under poor visibility conditions.[4] The federal government promised to take over the responsibility for these facilities as soon as the Depression was overcome and sufficient funds could be made available — which it did in 1937. The first experimental ATC unit proved a success, and other units were established. At the time, communications between pilots and ATC units were indirect, with airline dispatchers, airway radio

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[1] In 1925, the Air Mail Act had been endorsed which provided a regulatory framework.

[2] Eventually, Aeronautical Radio Inc. (Arinc) became an important intermediary actor for the airline industry with regard to coordination of implementation and use of airborne technologies.

[3] Two types of low-frequency radio navigation aids were used: nondirectional beacons and four-course radio range stations. The nondirectional beacon emitted a continuous signal that allowed the pilot to navigate by homing on the signal with an airborne direction finder. The radio range station was a further improvement in that it emitted a directional signal, forming four beacons aligned with respect to the compass, each defining a course. Pilots listened to a radio receiver and followed these radio beams from station to station along the route. The four-course radio range system was phased out beginning in 1950, after reaching a maximum deployment of 378 stations. Low-frequency nondirectional radio beacons are still in limited use in the United States and widespread use in other parts of the world (OTA, 1982).

[4] In good visibility conditions pilots were expected to "see and avoid" nearby aircraft. In other words, ATC services were only to be provided to aircraft flying under "instrument flight rules" (IFR) rather than "visual flight rules" (VFR).

operators, and airport traffic controllers as intermediaries between controller and pilot. ATC units were given flight plans and position reports, enabling controllers to keep track of the position of aircraft in airways using charts and blackboards. After the federal government took over responsibility for the emerging ATC system in 1937, en route controllers became federal employees, tower controllers at airports were certified, procedures were standardised, and a manual for ATC was established. In 1938, rules and regulations were consolidated into one ordered whole when the Civil Aeronautics Act was endorsed by Congress. Until then, aviation policy and regulation had been fragmented. The Civil Aeronautics Administration (CAA) was established to take responsibility for the long-term development of air traffic and ATC.[5] To provide the CAA with technological expertise and research capabilities, an Experimental Station was set up which was to become an important centre of expertise.

During the 1930s, several new intermediary actors emerged. In 1935 industry and government groups established the Radio Technical Commission for Aeronautics (RTCA) as an advisory body for the federal government in matters of ATC and other aeronautical issues. To assist to the federal government in the development and implementation of new technologies in the federal airways system, the Air Coordinating Committee was set up in 1937. The Committee included experts from industry and government. In the 1930s, other stakeholders also organised themselves in collective organisations like the Aircraft Owners & Pilots Association (AOPA), the Airline Pilots Association (ALPA), and the Air Transport Association (ATA). The emergence of organised interest groups is indicative of the socio-political context in which ATC was developed.

In 1937, with support from the Air Coordinating Committee, the Department of Commerce began a two-year comprehensive airways modernisation and extension programme in which the existing airway broadcast and radio range stations were converted to a simultaneous system of transmission enabling pilots to receive radio range signals and radiotelephone (voice) information on weather conditions at the same time. By the end of the 1930s, more than 160 transmission stations formed an extensive communications network, linking ATC units, communication stations, airport control towers, weather facilities, and military bases. This network made it possible to control all aircraft in airways which flew under instrument flight rules (IFR) — which was required in poor visibility conditions within control areas of ATC units.

By the 1940s, the United States ATC system consisted of two main subsystems: a federal airway system, which consisted of 25,000 miles of airways equipped with over 230 radio range stations and other navigation aids, and an airport/terminal system, which remained under local authority (but with federal advice). This "first generation" civil ATC system was a loosely coupled system, largely procedural, manually operated, and depended upon (indirect) voice

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[5] Initially, the CAA had been established as an independent authority, but was reorganised as an administration under the control of the Department of Commerce in 1940.

communication between pilots, dispatchers and controllers. Local control centres had considerable autonomy. The system had evolved in an ad hoc and incremental way. Developments had been driven by increases in air traffic and concerns about collisions and accidents.

In Europe, a patchwork of national ATC systems had been developed and implemented.[6] Since aircraft would cross national borders, interoperability of navigation and communication equipment was a concern, and procedures and ATC language were standardised. After the First World War, the International Commission for Air Navigation (ICAN) had been established to develop Air Navigation Regulations and General Rules for Air Traffic. The United States had not become a Member State, since transatlantic flights were not possible at that time, but its regulations were similar to international rules.

As transoceanic flights became possible, international coordination became increasingly important for the United States as well. At the end of the Second World War, a new organisation for international coordination and standardisation was established: the International Civil Aviation Organisation (ICAO). This time, the United States became a Member State. It was decided that each nation would retain its national sovereignty with regard to national airspaces. As a consequence, each nation was responsible for its own national ATC system.

During the war, new communications, navigation and surveillance technologies were developed for military purposes. Many of these could be deployed for civil ATC as well. In particular, radar and display technologies, and new VHF/UHF communication and navigation technologies were considered for implementation. The Civil Aeronautics Administration (CAA) with its Experimental Station, assisted and advised by the RTCA and the Air Coordinating Committee, assessed the opportunities to incorporate new technological options in the U.S. civil ATC system. Together with Raytheon Corporation, which had been involved in the development of military radar and display systems, the Experimental Station adapted military surveillance radar and display technology for the civil ATC system. Shortly after the war, surveillance radars were implemented at busy airports and at en route ATC centres. Radar and display technologies made it possible for controllers in towers and en route centres to see the aircraft they controlled on their radar displays. They no longer needed to keep track of aircraft by moving plastic markers ("shrimp boats") on charts. The CAA also introduced VHF/UHF communication technologies in the ATC system, enabling direct communications between controllers and pilots. Controllers could talk with pilots to give information (e.g. on weather conditions) and instructions, and make requests for flight information (e.g. on identity and altitude). With regard to navigation, the CAA wanted to equip the federal airway

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[6] For a detailed history of ATC in the Netherlands (placed in an international context) see De Roode (1988)

system with very high frequency (VHF) omnidirectional ranges (VORs) and distance measurement equipment (DME), as replacement for the low frequency four-course radio ranges.

Since navigation and communication technologies relied on compatibility of ground-based and airborne equipment, standardisation was a major issue, not only domestically, but also internationally. In 1948 the advisory body RTCA had strongly recommended a "common system" in which military and civil ATC were to be consolidated in one national ATC system. The RTCA guide plan was received with enthusiasm by Congress, and the Air Coordination Committee took RTCA's recommendations as a starting point to develop a detailed common system. However, integration of the civil and military ATC systems was hampered by conflicting interests and different priorities of different stakeholders. With regard to navigation aids, for instance, the CAA and its Experimental Station had been actively involved in the development of the VOR system, while the military were engaged in the TACAN system. During the Korean War in the early 1950s, the Department of Defence accelerated the development and installation of its TACAN system, which was better suited for military aircraft than VOR since it required smaller, lighter airborne equipment. After the Korean War, the common system reappeared on the agendas of the Department of Commerce and the Department of Defence. A committee with experts from both Departments was unable to determine how to proceed. The stakes had become high for both military and civil users, and irreversibilities had occurred. Eventually, the Air Coordinating Committee fabricated a compromise in which the distance measuring function of TACAN was combined with VOR in a combined navigation aid (VORTAC).

On an international level, the CAA became engaged in a standardisation battle within the ICAO, whose long-term aim was to develop a world-wide air navigation system based on airways with ground services and facilities. Different countries had developed different alternatives which were proposed as candidate standard navigation aids. The CAA had to act swiftly, also because the airlines were anxiously awaiting an official ICAO standard before investing in equipment. Eventually, after exhaustive discussions within ICAO, it was agreed that the standard short-range navigation aid should be VOR, where necessary supplemented by distance measuring equipment (DME). This decision to designate VOR as standard short-range navigation aid led to controversies which lasted until 1954. The United Kingdom, in particular, was furious and accused the ICAO of being biased. The British consistently argued that there was a special requirement for a short-range navigation aid in Europe which could provide area coverage, because of the particularly dense criss-cross pattern of potential air routes in Europe. This pattern resulted from the many population centres distributed nearly evenly throughout Europe and which, when served by point-source aids like VORs, would impose inordinate high economic demands on national governments. In addition, there were possible technical difficulties related to frequency assignment and siting. British proposals to standardise the Gee system, and later the Decca system, as a supplementary navigation aid for

Europe were to no avail. As soon as the ICAO made a provisional decision to adopt the American VOR system, airlines had started to invest in VOR compatible equipment, and several national aviation authorities started with the implementation of VOR stations. This created irreversibilities which reduced the room for manoeuvring with regard to the development of navigation aids. Thus, international interoperability requirements resulted in a world-wide application of one type of navigation equipment.

Similar controversies emerged around standardisation of landing aids. On a national level, the CAA, airlines (organised in ATA) and commercial pilots (organised in ALPA) preferred the Instrument Landing System (ILS) which incorporated additional aircraft instruments to assist the pilot in landing. The military and owners and pilots of private aircraft (organised in AOPA), on the other hand, preferred a ground-based Ground Controlled Approach (GCA) system which did not rely on special onboard equipment.[7] Eventually, in the 1950s ILS was chosen as the standard, also within the ICAO. The ICAO proved to be capable of handling these issues and established itself as the international forum for aviation matters. In many cases, American candidate standards were adopted as international standards. ICAO decisions set in motion a series of global purchasing and implementation schedules. Network externalities and sunk investments virtually ruled out any further consideration of alternative systems in the nearby future.

With the implementation of radar surveillance in terminal areas and en route centres, direct communications between controller and pilot, airways marked by VOR/DME, and instrument landing systems, a "second generation" ATC system had emerged in the United States and elsewhere. The second generation was a patchwork of loosely coupled (sub)systems. Its performance (in terms of safety and efficiency) depended to a large extent on humanware, i.e. manual operations by trained air traffic controllers and standardised procedures. Controllers collated information from a wide variety of sources such as radar, voice communications and flight plans, in order to maintain a sense of the location, trajectory and altitude of aircraft. The architecture of the second generation ATC system was shaped by the technological options which had become available, largely from military domains. Interoperability requirements, caused by aircraft flying from one location to another, had induced international standardisation efforts. These standardisation processes were highly politicised as different stakeholders tried to influence outcomes. The level of cosmopolitanisation can be characterised as low, as different countries followed their own approaches to the design and implementation of ATC systems. Knowledge activities on the level of the overall architecture were ad hoc and reactive — rather than systematic or pro-active. However, (anticipations on) international

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[7] See Conway (2001) for a detailed analysis of "the politics of blind landing".

standardisation created mutual dependencies between national ATC system developers, and these created affordances for interactions and coordination.

7.2.2 "Third generation" of ATC

While the implementation of the second generation ATC was well underway (and would last until the end of the 1960s), air traffic was growing to such an extent that the ATC system became overloaded. Especially the introduction of jet aircraft by the airlines in the late-1950s added additional complexities to the control of air traffic. In particular the combination of fast jet aircraft and relatively slow conventional aircraft made separation of aircraft more complex. A disastrous mid-air collision in 1956 above the Grand Canyon was an undeniable signal that the ATC system was not up to its demanding task. It could not be dismissed as an incident as sixty-five mid-air collisions had occurred in the United States between 1950 and 1955. After Congressional hearings that followed the Grand Canyon collision, the federal government decided that modernisation of the ATC system was required and that funding had to be increased. A Study Group of experts was established to make recommendations for modernisation. To solve the critical problem of separation between aircraft, especially between slower (propeller) and faster (jet) aircraft, it was recommended to divide the airspace in segments ("funnels" and "cylinders") in which flying under instrument flight rules (IFR) was mandatory, regardless of visibility conditions. At the end of the 1950s, such "positive control" was established in designated parts of the airspace, in particular in airways and in terminal areas around major airports. The Study Group also recommended the implementation of "secondary surveillance radar". This radar system was based on the military IFF ("identify, fried or foe") system which was used to distinguish enemy planes from friendly planes on radar displays. In positive control segments of airspace, aircraft would have to be equipped with transponders which could be interrogated automatically by ground radars for their identity. The effect would be that the voice communications workload of controllers would be significantly reduced.

To manage the modernisation and maintenance of the American ATC system, the Study Group recommended that an independent Federal Aviation Agency (FAA) had to be established to succeed the CAA.[8] The existing Experimental Station was to be consolidated in a new National Aviation Facilities Experimental Center (NAFEC) which had to support the FAA in its modernisation task.[9] The FAA was to be made responsible for developing and consoli-

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[8] In anticipation of the establishment of the FAA, a temporary Airways Modernisation Board had to be organised to unite distributed responsibilities for system development and selection. The Airways Modernisation Board was established in 1957 and was charged with the development and modernisation of the national system of navigation and ATC facilities.

[9] In 1980, NAFEC was renamed FAA Technical Center, and in 1996 it became FAA William J. Hughes Technical Center.

dating the requirements for future systems of communications, navigation, and surveillance. It was deemed necessary "to reverse completely the approach of having the operations of the air traffic control system governed by the kind of tools the engineers give the operators."[10] Instead, ATC system operators should develop broad performance specifications for the equipment they needed, and then the engineers should design and develop such equipment. Thus, the role of controllers in the design of the ATC system had to be increased. In 1956 controllers had organised themselves in the Air Traffic Control Association (ATCA). In the 1960s, the ATCA would evolve into a professional organisation with membership open to providers of ATC services, system architects, equipment manufacturers, system operators, as well as ATC users. Its main objective was to create and disseminate knowledge of the control of air traffic "in all its phases and applications". It promoted circulation and aggregation by organising conferences and symposia and publishing a variety of journals, proceedings, and other periodicals.[11]

In 1958, two years after the Grand Canyon collision, the Federal Aviation Act was signed which repealed older Acts and previous Presidential reorganisation plans, and created a coherent whole of aviation rules and regulations. With the new Act, the FAA was established as an independent central organisation in civil *and* military aviation. (In Europe, such integration was not realised). It became a powerful actor in the aviation community, even while its reliance on federal funding made it dependent on political endorsement and put constraints on its room for manoeuvring. Modernisation of the ATC system remained a highly politicised undertaking in which various stakeholders tried to shape the decisions.

In the late-1950s, automation of controller tasks was identified as a promising solution to modernise the ATC system. The FAA undertook its first trials with a general purpose IBM-650 computer in the late 1950s. Experiences with the Semi-Automatic Ground Environment (SAGE) air defence system had demonstrated that computers could be used in real-time systems. SAGE had been designed to intercept enemy bombers, and used multiple radar sites to display all the aircraft within a designated area on the radar screen, making it possible for military controllers to vector air defence fighters toward invading enemy aircraft. This system of radar stations was linked to a central digital computer and it involved an information-processing and real-time control system (Hughes, 1998). During the 1950s when full integration of the military and civil ATC system was an objective, it had been considered to integrate the civil ATC system in SAGE. While this integration had not happened, SAGE still provided a model for a semi-automated civil ATC system. Organisations which had been involved in SAGE, like MIT Lincoln Laboratory and MITRE, would come to

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[10] FAA Historical Chronology 1926-1996.

[11] Website of ATCA.

play important roles in the design and development of ATC systems in the United States.

Automation of air traffic controller tasks was not only considered in the United States, but in Europe as well. Initially, computer manufacturers had not been active in the field of ATC, because this market was considered too small and too complicated. Ongoing sophistication and miniaturisation of electronic data processing equipment and cost reductions made it possible for computer manufacturers to produce equipment which was also of interest to civil ATC where large amounts of flight data had to be accepted (in the form of flight plans, position reports etc.), recorded and processed (in real-time) in order to exercise the required control functions. Automation projects were undertaken in the late 1950s and 1960s in several countries, including the United States, the United Kingdom, France, West Germany and the Netherlands.[12] In small groups of highly specialised experts it was studied what kind of equipment could be used to automate controller tasks (Schouten, 1969). These groups followed their own approach and did not collaborate although there were informal interactions and exchanges to "to find out what the others were doing." (Schouten, 1969: 36). As a result, each nation developed and implemented its own incompatible system — using prototyping and/or large-scale simulations. Given the strategic importance of the undertaking, most countries placed orders with their national industries only. At the same time, it was anticipated in the 1960s that "the fast development of air traffic [would] ultimately call for an uniform ATC system for the whole world." (37).

The introduction of automation in civil ATC systems would increase the need for coordination between different countries. As flexible "humanware" was replaced by relatively inflexible hard- and software, the tightness of the coupling within and between national ATC systems increased, and this would necessitate a well-considered and coordinated approach to ATC system design and development. Within the European section of the ICAO, the use automated data processing was discussed in 1958. The ICAO was to play a central role in developing standards for data formats and messages. Interoperability between equipment of different manufacturers was a major concern, since

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[12] The Netherlands were among the pioneering nations in Europe. A domestic manufacturer, Hollandse Signaal Apparaten (HSA), had approached the Dutch ATC authorities in 1956 with a proposal to develop a dedicated ATC computer. HSA thought to base an ATC system on military air defence technology in which it had built up considerable expertise. (The champion of HSA's project was a former officer of the Royal Navy.) It wanted to develop a digital system which could automatically calculate the flight path of an aircraft spotted by radar (Mom *et al.*, 1999). HSA had followed FAA's try-outs with IBM-650s with interest and concluded that programming of a general purpose computer for real-time applications was very difficult. In collaboration with the Dutch ATC authorities, HSA started to work on a special purpose computer to automatically print flight data on "flight strips". The Signaal Automatic ATC (Satco) system was implemented at Schiphol Airport in 1960, and during the 1960s, Satco was further upgraded with display of flight information on flight progress boards and an automatic conflict search. After a three-year trial period, the new Satco system was implemented in 1968. (See Schouten (1969) and Mom *et al.* (1999) for details on Satco).

equipment of adjacent ATC units in neighbouring countries needed to correspond with each other. Such interoperability was jeopardised by the practice of national governments to award large ATC contracts to domestic manufacturers. In addition, ATC automation could only be realised step-by-step over an extended period of time. Automated and non-automated ATC facilities would be existing side by side for many years. It was important that non-automated ATC units were not faced with an inordinate high workload, or specific supplementary procedures, simply because they were required to cooperate with an ATC unit which used automatic processes.

While the introduction of jet aircraft had resulted in modernisation efforts in the United States, in Europe it resulted in attempts to improve international coordination in the late-1950s In 1958, during a regional ICAO meeting, Belgium, Luxembourg, the Netherlands and West-Germany agreed to do a joint study on the desirability and feasibility of an internationally coordinated ATC service. This resulted in a convention, signed by Belgium, the Netherlands, Luxembourg, West-Germany, France, Great Britain and Ireland, which provided for the establishment of a supranational organisation. In 1963 Eurocontrol was established. Because nation states were reluctant to reduce national sovereignty with regard to their airspaces, the objective of Eurocontrol was modest: its objective was to oversee ATC in the upper airspace of Member States. Not until the 1980s, the primary goal would become the development of a coherent and coordinated ATC system in Europe.

In December 1960, another major mid-air collision occurred in the United States, this time above New York. It caused public concerns about the safety of air travel, and the federal government was forced into action. The FAA was asked by the federal government "to conduct a scientific, engineering overview of our aviation facilities and related research and development, and to prepare a practicable long-range plan to insure efficient and safe control of all air traffic within the United States."[13] The FAA established the Project Beacon Task Force with the commission to draw up new recommendations for modernisation of the ATC system. The Task Force made a study of technological options and opinions of stakeholders. There were several conditions which had to be taken into account. Third generation equipment had to be backwards compatible with existing equipment. During the transition phase, second and third generation equipment had operate side by side without jeopardising the reliability of the ATC system. There were various stakeholders with diverging interests. The Aircraft Owners and Pilot Association (AOPA) lobbied to keep the cost of mandatory equipment as low as possible in an attempt to keep flying affordable. Airlines wanted a more efficient ATC system and welcomed more sophisticated equipment. Air traffic controllers (organised in ATCA) wanted to have their

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[13] FAA Historical Chronology 1926-1996.

workload reduced. Eventually, the Task Force concluded that the FAA urgently needed an overall systems plan in which all subsystems were designed as part of an overall "third generation" systems architecture.

An important element in Project Beacon Task Force's recommendations was to upgrade secondary surveillance radar, which was already being installed in aircraft, in such a way that aircraft could answer to interrogations by ground stations not only with identification codes, but also with altitude information. This would reduce voice-communications workload of controllers considerably and would not incur too much extra cost for aircraft owners. Moreover, it meant that existing, proven technologies could be used which could provide an immediate solution for acute problems. A sophisticated automated radar system that could measure altitudes of aircraft, which was under development at FAA's National Aviation Facilities Experimental Center (NAFEC), was rejected because it was found to be too uncertain, too radical and too expensive.

Another key element in Project Beacon Task Force's recommendations was that computer systems for both the "en route" part as well as the "terminal area" part of the ATC system had to be developed and implemented. The FAA developed the so-called National Airspace System (NAS) En Route Stage A programme for the twenty en route control centres and Automated Radar Terminal System (ARTS) programme for the terminal control centres. To ensure that various elements of the modernisation programme were coordinated and integrated into an overall system, the FAA appointed the systems engineering organisation MITRE. MITRE was a not-for-profit organisation which had been created in 1958 by MIT Lincoln Laboratories to handle SAGE integration. MITRE collaborated with FAA's NAFEC. Using its expertise in systems integration, MITRE would also become active outside the United States in the 1970s.[14] Thus, it became an important centre of systems engineering expertise in the international field of civil ATC.

During the first phase of NAS En Route Stage A programme, new systems were developed and implemented to automate the processing of flight data. This new system relieved controllers of several bookkeeping and clerical tasks. Flight data was automatically updated and distributed within a centre's control sector as well as between control centres. IBM's Federal Systems Division had been awarded the contract to develop and implement mainframe computers at the en route centres. In 1970, almost ten years after Project Beacon's recommendations, the first IBM 9020 computer (based on IBM's successful 360 system) and its associated software programme became operational at the Los Angeles control centre. These systems were replicated in the other twenty en route centres. In 1973, the last IBM 9020 system was installed. During the second phase of the NAS En Route Stage A programme, also the processing of

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[14] The United Kingdom became MITRE's first foreign ATC client in 1973. (See website of MITRE for history and overview of its activities in ATC).

radar data was partly automated. Automatic aircraft tracking and computer-generated alphanumeric displays fed by digitised radar data were developed and implemented. Also weather information could be displayed. After extensive testing of prototypes, the second phase was completed in 1975 when all en route centres were equipped with radar data processing systems. In the third and final phase, advanced communication technologies were implemented to improve communications between controllers, pilots and computers. Also computer-generated conflict-prediction and conflict-resolution capabilities were developed and installed.

The ARTS programme for terminal control centres provided for similar functionalities as the NAS En Route Stage A programme. It included primary and secondary surveillance radar tracking, digital displays, weather contours, multiple radar processing, metering and spacing. The basic contract was awarded in 1969, and the first ARTS III system was installed in 1973. Two years later the programme was completed the system was installed in sixty other centres.

With the automation programmes for both the en route centres as well as the terminal centres in place, the FAA had achieved a semi-automated ATC system which was based on a combination of radar and computer technology. The automation process, especially of radar data processing, had proved a complex, lengthy and costly task. There had been delays, caused by budget cuts and unexpected technical difficulties. The extreme performance and safety requirements had proven to be a major challenge for the FAA and its contractors. The software written for ATC was the most sophisticated of its time. With these automation programmes completed, irreversibilities within the ATC system increased. As it turned out, the FAA had heavily invested in computer systems that were difficult to upgrade or expand. The ATC system had become a more tightly interconnected system of subsystems, including primary and secondary surveillance radar systems, computers, displays, weather systems, communication systems. Changing one element in the ATC system, would require changes in other elements as well — while the system could not be switched off. Thus, future modernisation efforts would become increasingly difficult, and would require careful planning and coordination. In addition, the increasing use of automated information and communication systems meant that international coordination and standardisation became increasingly important. In the 1970s and 1980s. the effects of this increased complexity on modernisation efforts would become manifest.

7.2.3 "Upgraded third generation" of ATC

Although the automation programmes NAS En Route Stage A and ARTS were successfully implemented in the mid-1970s, they had been hampered by delays and cost overruns. While the automation programmes went slower than planned, the air traffic volume was growing faster than anticipated. In the late 1960s, controllers began to protest against their overload of work, especially when the FAA laid off personnel to reduce cost. At the same time, yet another major accident occurred which seemed to underline that safety could not be guaranteed. Shortly before, in 1967, the Department of Transportation (DoT) had been established, and the FAA had been reorganised as an Administration (rather than an independent Agency) under DoT. In 1968 DoT set up the ATC Advisory Committee of experts to study how the ATC system could be modernised. Recognising that air traffic would increase substantially in the 1970s and that modernisation had become a highly complex undertaking which would require long-term plans, the ATC Advisory Committee was asked to draw up requirements for the ATC system of the 1980s and beyond. The ATC Advisory Committee concluded that the emerging third generation had to be upgraded in order to meet the traffic demand forecasts for the 1970s and 1980s. Based on growth projections, three critical problems were identified: the shortage of terminal capacity, the need for new, more efficient and accurate means of assuring separation between aircraft, and the limited capacity and increasing cost of the ATC system. Several procedural and technological solutions were recommended to solve these problems. Whereas previous modernisation programmes had suffered from inadequate funding, this modernisation programme was accompanied by a new law which ensured funding for at least the next five years.[15]

The ATC Advisory Committee developed long-term requirements which were to guide technological work by research and systems engineering organisations, including FAA's NAFEC, MITRE and MIT Lincoln Lab, and industry. MIT Lincoln Lab played an important part in the translation of requirements in a fully specified future ATC system. MIT Lincoln Lab was known for its expertise on radar and communication technologies which it had accumulated while being involved in SAGE. During the Vietnam War, funding of fundamental R&D by the Department of Defence decreased, and military research centres like Lincoln Lab were looking for civil applications of their knowledge bases. In effect, Lincoln Lab became FAA's technical arm for the design and specification of the ATC architecture and it became an important knowledge producer at the level of the overall architecture.

Lincoln Lab started with a key recommendation of the ATC Advisory Committee that existing secondary surveillance radar technology should be further upgraded into an air-to-ground "data link" in order to further reduce the controller's voice communications workload and to increase the ATC system's capacity. An incremental approach was chosen in which was built on existing technologies. Backward compatibility was an important requirement because is made transition to a new generation less complicated, and also because it would be less difficult to create acceptance among aircraft owners and pilots. The capacity of existing secondary surveillance radar systems was inherently limited because it broadcasted interrogations from the ground to all nearby aircraft, and when many aircraft replied simultaneously, replies could overlap and get garbled. This could cause dangerous situations since aircraft could get lost on radar

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[15] In 1970, the Airport and Airway Development Act / Airport and Airway Revenu Act was signed.

screens. The broadcasting feature was an inheritance of the military IFF system which had not been designed to function in crowded airspace. Lincoln Lab developed a "discrete addressing" capability which allowed ground stations to interrogate one specific aircraft at a time. Discrete addressing made it possible to use the interrogation/reply system for a broader range of information exchange even in crowded airspace. Lincoln Lab's discrete address beacon system (DABS) could handle identity, position as well as altitude information and it allowed for automation of ground-air data communications. Aircraft could provide the ATC system automatically with accurate position and track data thanks to advances in avionics (i.e. electronics designed for use in aircraft). A next step was to use these data as inputs in a ground-based automatic collision-avoidance system. Thus, secondary surveillance radar could be upgraded into a key element in the ATC architecture, allowing for automatic data interchange and automatic collision avoidance.

In 1975 Lincoln Lab delivered its final design of DABS to the FAA. Subsequently, competitive contracts were awarded to firms for the development of engineering models of ground sensors and compatible airborne transponders. The implementation of DABS (or Mode S, as it was to be called in ICAO nomenclature, with S for "selective addressing") was not an easy affair. It was estimated that by the time the new system could be deployed, there would be more than 200,000 aircraft equipped with 'old' transponders and over 500 ground stations would need to be upgraded. Various users of the ATC system, in particular owners of smaller aircraft, preferred cheaper, less innovative technological alternatives. In addition, the FAA had to find international acceptance of its system and, in particular, its data formats, in order to ensure international interoperability. ICAO standardisation was a slow bureaucratic process, and pending ICAO's final decision, Lincoln Lab and the FAA made sure DABS was compatible with existing systems around the world by keeping the international aviation community up to date by providing information on their progress. They exchanged information with the United Kingdom and the Soviet Union which were working on similar systems. Eventually, the implementation and acceptance of Mode S took many years, until the mid-1980s, which illustrates that changing the ATC system had become a highly complicated and politicised process.

Since the late 1960s, much was expected of collision avoidance systems in the aviation community. The idea of collision avoidance systems dated back to defence projects on missile interception systems in the 1950s.[16] The knowledge and expertise on interception of flying objects could also be deployed for systems that had to avoid collisions between flying objects. Several manufacturers

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[16] In 1955 Bendix Avionics had published *The physics of collisions* which included an algorithm that defined the rate of closure between approaching flying objects. This algorythm was used in many systems that were developed since then. Other systems used approaches based on distance measurement or time-to-escape.

had worked on airborne collision avoidance systems during the 1960s. Most of these systems determined distance between aircraft by timing of replies to interrogations made by one aircraft to its surrounding aircraft. In the early 1970s, the FAA was criticised for its failure to achieve prompt deployment of an airborne collision avoidance system. After Congressional hearings on aircraft collisions in 1971, the FAA was requested to undertake an evaluation of three forms of these systems developed by Honeywell, McDonnell-Douglas and RCA.[17] After extensive testing by FAA's NAFEC, the FAA concluded that none of the systems was good enough, and that a combination of ground-based and airborne collision avoidance would be the best way to proceed. The FAA argued that it was difficult for pilots to oversee all nearby aircraft, and coordination and direction of several aircraft required that one person (the controller) had authority over others (the pilots in the controllers sector). This line of reasoning fitted with FAA's control philosophy, in which decision-making was centralised in control centres.

While working on DABS, MIT Lincoln Lab became involved in the development of collision avoidance systems using its expertise in defence projects. It developed a beacon collision avoidance system (BCAS) which was based on existing systems to avoid extra equipment costs for aircraft owners. In addition, BCAS was also designed to be forward compatible with new Mode S transponders. BCAS made use of their reply signals of transponders (which were already installed in all airline, military and most general aviation aircraft) to determine "intruder range" and altitude of nearby aircraft.[18] Thus, any aircraft equipped with BCAS would be protected against the majority of other aircraft. Discrete addressing techniques permitted two conflicting BCAS aircraft to coordinate escape manoeuvres. In crowded airspace, however, self-contained airborne versions caused radio interference, and solving that problem required the deployment of an expensive ground-based automatic traffic advisory and resolution service (ATARS) in order to assure safe separations. Because of these costs, the FAA was slow to endorse BCAS. After a dramatic mid-air collision in 1978 and ensuing criticisms, the FAA drew up a new comprehensive programme in which all transponders installed after mid-1982 would have to incorporate Mode S which would provide an automatic data link with a ground-based collision avoidance system. All airliners were obliged to install BCAS by

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[17] FAA Historical Chronology 1926-1996.

[18] "Active" BCAS onboard aircraft would give information on positions of nearby aircraft. "Full" BCAS would also listen in on replies to interrogations from the ground, correlating this replies to determine bearing as well as range. Also a "passive" BCAS was developed it never went into full production because it was considered too complex and would not work over the ocean or in areas with limited radar coverage. Passive BCAS could locate and track nearby aircraft based on listening for transponder replies from other nearby aircraft to two or more ground interrogators. By timing the receipt of these ground interrogations and replies from other aircraft, and using the known positions of the ground interrogators, a passive system calculated the relative positions and altitudes of other aircraft.

1985.[19] These proposals met with a massive negative response, especially from the Aircraft Owners & Pilots Association (AOPA) because it was believed these plans would make flying too costly. Faced with such negative response, the FAA withdrew most of its plans. In 1981, the FAA unexpectedly decided to drop BCAS altogether. Instead it preferred a new air-to-air traffic alert and avoidance system (TCAS) which had been developed by MITRE and Lincoln Labs.[20] TCAS built on the BCAS design but provided additional capabilities using Mode S. The FAA decided to adopt TCAS because it did not require new expensive equipment on the ground. The FAA assumed responsibility for supporting the necessary research, developing prototype equipment, demonstrating the operational and technical feasibility of the TCAS concept, generating national standards for the equipment, and certificating TCAS-equipped aircraft for normal operation. Implementation of TCAS would prove to be a slow process, which again illustrates how complicated ATC system development had become.[21]

The sudden move of the FAA to support TCAS, rather than a combination of an airborne and a ground-based system, was prompted by a need to reduce costs of (new) ground-based equipment. At the same time, however, it meant a shift in the control philosophy from a centralised, ground-based approach to a more distributed approach in which pilots received more information and responsibilities. This shift had been made possible by developments in avionics which provided pilots with more information on nearby aircraft. Until then, ATC system development had been characterised by increasing centralisation. ATC was primarily ground-based, highly centralised, and placed great emphasis on standardised behaviour by airspace users. Controllers on the ground had all the information, and pilots flying in positive control airspace were completely dependent upon the information and directions given to them in order to avoid collisions. Centralisation had been advantageous for the FAA because it consolidated functionally similar activities and it allowed for technological specialisation. Thus, centralisation had contributed to higher safety as well as greater efficiency. In line with their central control philosophy, the FAA had established a Central Flow Control facility in 1970, to enable strategic,

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[19] A proposed national standard for BCAS had been issued earlier in 1978.

[20] Originally, TCAS had stood for Threat Alert and Collision Avoidance System.

[21] The 1987 Airport and Airways Capacity Expansion and Improvement Act established deadlines for completing development and installing TCAS II on commercial transports. The FAA had to approve and validate the TCAS II performance standards by 1989. The FAA finished its regulatory requirements for development on time in 1988. The remaining FAA responsibility for establishing TCAS II was to test and evaluate TCAS II equipment that met the latest standards. This testing had to be done at the FAA Technical Center in 1989. Each passenger-carrying aircraft with more than 30 seats would have to be equipped with TCAS II to operate in U.S. airspace after December 30, 1991 (OTA, 1989).

rather than tactical, air traffic management.[22] This central facility took over from the en route centres some of the responsibility for restricting the number of aircraft moving from the control of one centre to another.[23] Potential trouble spots were detected and solutions, such as flow-control restrictions or rerouting, were suggested to the centres.

In the 1980s, the trend towards further centralisation was reversed as pilots were allowed to cooperate with controllers rather than just follow instructions. In addition to airborne collision avoidance, "area navigation" is another example of a technology that enhanced pilots' responsibilities. Until the 1970s, pilots flying in upper airspace were obliged to fly "zigzag" tracks determined by the position of navigation aids. Area navigation provided more lateral freedom because it did not require aircraft to fly tracks directly to or from radio navigation aids.[24] Thus, a route structure could be organised between any given departure and arrival point to reduce flight distance. Other applications of area navigation included the capability for aircraft to approach terminal areas on varied pre-programmed arrival and departure paths to expedite traffic flow, and the capability for instrument approaches certain airports which were not equipped with instrument landing aids.

During the 1970s and 1980s, an upgraded third generation ATC system was developed and (slowly) implemented. This system was characterised by semi-automated systems in control centres,[25] upgraded secondary surveillance radar (Mode S data link), an airborne collision avoidance system (TCAS), and area navigation. The ATC system had evolved into a large information processing and decision support system for controllers and (increasingly) for pilots. With the involvement of knowledge producers such as MITRE, MIT Lincoln Lab and NAFEC, a more planned and coordinated approach to the design and implementation of the ATC architecture had been introduced. MITRE, in par-

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[22] During a three-month test in 1970, the new central flow facility had proved its worth in reducing delays, and had been invaluable in monitoring and rerouting traffic during the controller strike (FAA Historical Chronology 1926-1996).

[23] An analysis of the causes of the air traffic delays showed that central coordination of the en route centres could help to prevent isolated clusters of congestion from disrupting the overall traffic flow. En route ATC centres lacked information on the overall traffic flow. Therefore, they tended to be overdefensive. For example, when a build-up of traffic forced one centre to restrict the number of incoming aircraft from an adjacent centre, the adjacent centre might fear an impending traffic build-up in its own area and hence institute restrictions against yet another centre. The spreading restrictions could eventually affect IFR aircraft throughout the ATC system (FAA Historical Chronology 1926-1996).

[24] Area navigation used radio signals from (nearby) navigation aids on the ground and/or a self-contained system onboard an aircraft which could determine the position. Navigation systems could provide an area navigation capability include VOR/DME, DME/DME, LORAN C, GPS, OMEGA and self contained Inertial Navigation Systems (INS) or Inertial Reference Systems (IRS).

[25] By 1980 computers were extensively used throughout the ATC system: to process flight plans, to correlate radar and transponder returns, to filter out extraneous signals that could obscure controlled aircraft, and to generate displays on the controller's console (OTA, 1982).

ticular, followed a systems engineering approach which made a systematic (rather than ad hoc) approach to ATC architecture design possible. This allowed MITRE to exploit its experiences in other countries as well. It signalled the beginning of a cosmopolitanisation process in the field of ATC, in which architectural knowledge was produced which could transcend national ATC system specifics.

7.2.4 "Fourth generation" of ATC

In the early 1980s, with the upgraded third generation ATC system almost fully implemented, the FAA started a new round of modernisation. Especially the replacement of the IBM 9020 computer systems in the control centres with new up-to-date systems was urgent. To guide the transition to a "fourth generation" ATC system, the FAA, supported by MITRE, published its National Airspace System (NAS) Plan as a comprehensive 20-year blueprint, to be updated annually, in the early 1980s. In the NAS Plan the ATC architecture was perceived as an interconnected whole of interoperable elements which needed to be taken into account simultaneously. Interoperability was a critical requirement: not only interoperability within the ATC architecture between different subsystems, but also backwards compatibility between old and new equipment (which needed to work in parallel during transition because ATC could not be temporarily switched off), interoperability with the military ATC system,[26] as well as international interoperability.[27] There were also economic constraints, posed by availability of funding for design, procurement, installation, operation and maintenance of facilities on the ground, and by costs that aircraft owners were able, or willing, to bear for airborne equipment. Finally, national security was and remained a major concern for the FAA.

Key elements of the NAS plan were replacement of outdated computer systems, consolidation of the terminal area and en route facilities into new "area control facilities", mandatory use of Mode S as a key component for digital data link and collision avoidance, downgrading of primary surveillance radars to a backup facility, and introduction of a new, much more flexible, microwave landing system to increase terminal capacity.

In spite of FAA's ambition to provide a comprehensive plan for a future ATC architecture, the NAS Plan received various criticisms, among others from the Congressional Office of Technology Assessment (OTA). OTA concluded that "[a]s a blueprint for the modernisation of the ATC system, the 1982 NAS Plan does not provide a clear sense of the priorities or dependencies among its various program elements. (…) Given the complexity and magnitude of this

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[26] The civil ATC system was obliged to meet the needs of the military in time of war.

[27] In addition, existing procedures with regard to the way the airspace was organised in airways and positive control areas, and minimum horizontal and vertical separation standards also had to be taken into account.

undertaking, FAA may have set itself an overly ambitious schedule for implementing the proposed improvements." (OTA, 1982b: 4). In addition, the OTA noted that satellites had been left out of the plan without good reasons. In the 1984 revision of the NAS Plan, the Global Positioning System (GPS) was mentioned as a future supplemental navigation system for civil aviation.

A crucial part of the NAS plan was the replacement of the old IBM 9020 computer systems in the control centres which dated back to the 1960s. Since then, significant advances in information and communication technologies had been made. The new information and communication systems had to anticipate on, and be forward compatible with, FAA's future concept of automated en route ATC (AERA), a concept which had to be realised by the year 2000. Until the late 1970s, the FAA had favoured a full replacement strategy in which all hardware (including display systems) and software were to be replaced in one step. By 1982, however, the FAA had come to realise that this approach was very risky and complicated, given the stringent safety requirements and the technological complexities involved. A "hardware-first" approach was chosen, which meant that software would be "rehosted" on new hardware, before being upgraded. Thus, the new computer system had to be compatible with the existing software package which had been developed by IBM. IBM and Sperry Corporation were awarded two competitive contract for the design of a new mainframe system. IBM's design won, and IBM was awarded the replacement contract. The replacement was relatively unproblematic. During 1987 and 1988 all twenty en route control centres were provided with new IBM systems.[28] The next, more complicated phase involved the development and implementation of new software packages, new displays, and other peripherals. The goal was to provide each controller with a new sophisticated "sector suite" workstation. In 1984, both IBM and Hughes Aircraft Corporation had been awarded design contracts. Four years later, IBM won the $3.55 billion contract to develop, deploy, and service the new sector suites. This programme, however, ran into serious delays and major cost overruns, and in 1993 the FAA had to conclude that a complete overhaul of the programme had become inevitable. The sector suite workstations had to be downgraded substantially.[29] Consolidation of the terminal area and the en route control facilities was cancelled, which meant that terminal area centres had to make do with upgraded ARTS systems for the time being. Meanwhile, the primary contractor IBM, sold its responsible business unit to Loral Corporation, which, together with the FAA, formulated a less

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[28] The Host computer was used to compute radar tracks, maintain a database of flight plans, and issue safety warnings — such as conflict alerts and minimum safe altitude warnings. The Host computer system contained half a million lines of Jovial code and assembly language that was first installed in 1972 and ported from IBM 9020 onto IBM 3083 computers, starting in 1985. The Host computers had 16 MB of RAM, which eventually became a serious limitation (Perry, 1997).

[29] According to a controller, the Host software had so many patches, no one knew how it worked. "We can't change anything; no one dares touch it, because if we break it, we're gone."(Perry, 1997).

ambitious programme: the display system replacement (DSR). To replace ARTS in the terminal area centres, a standard terminal automation replacement system (STARS) procurement programme was developed. Eventually, in the mid 1990s, Lockheed Martin became the contractor for the DSR workstations and a team led by Raytheon was awarded the contract to build and install STARS equipment. By that time, the NAS Plan had been succeeded by a new "NAS Architecture" programme (see next section). After the failed system replacement programme under the NAS Plan, the FAA decided to prefer commercial off-the-shelf equipment rather than dedicated computer systems. Such systems could be upgraded and expanded more easily. They could function as more flexible elements in an architecture which was becoming increasingly complex and interconnected.

In 1994, OTA again released a critical report in which it was stated that ATC system lagged behind comparable telecommunications, computing, and information systems that were used in other fields. The chronic delays in ATC system development and implementation, were attributed to shortcomings in analysing and establishing operational requirements. According to OTA's analyses, fundamental changes in the overall development process at FAA were required for major improvements to the ATC system, in addition to increased spending and easier procurement with respect to technology R&D (OTA, 1994). Also the General Accounting Office kept an extra critical eye on the spending of public money by the FAA, after billions of dollars had been spent to no avail on the automation programme. Faced with such criticisms, the FAA developed a new credible modernisation programme in which all projects could be justified in terms of their contribution to the overall performance (safe and efficient air traffic), and in which stakeholders were given the opportunity to give comments.

7.2.5 "Fifth generation" of ATC

The problematic implementation of the NAS Plan and its updates during the 1980s and early 1990s, occurred in a context in which the ICAO put forward a new global ATC system concept in which satellites played a central role. The central role of satellite technology reinforced the ongoing internationalisation of ATC, because it made "seamless" global ATC possible in principle. The national approach to ATC system design was identified as a major impediment to an increase in efficiency and safety in ATC, especially in Europe were a patchwork of systems had evolved. By the 1980s, the complexity and capital intensiveness of the ATC system had increased to such an extent, that it became increasingly difficult and expensive for single civil aviation agencies to independently develop, build, and operate all of the elements of a next generation ATC system. Thus, increased costs and complexity created affordances for coordination and collective action. ATC systems had always been the responsibility of each nation under its agreement with the ICOA, and national governments financed, owned, and oversaw virtually all of the facilities and equipment necessary to control traffic in their airspace. The prospect of a global satellite-based ATC system made such a national approach to ATC inefficient.[30]

In response to projected growth rates of international air traffic in the early 1980s, the ICAO had concluded that an internationally coordinated approach was needed to increase the capacity of airspace systems. In 1983, a Special Committee was set up to assess existing air navigation systems around the world and to make recommendations for a coordinated, evolutionary development of air navigation into the next century. In 1988, the Future Air Navigation System (FANS) Committee published its findings and concluded that existing systems were inherently limited by a number a factors,[31] and identified several difficulties with regard to implementation and operation of systems in a consistent manner around the world. In order to increase the capacity of airspace systems and to improve systems integration and organisational coordination, the FANS Committee proposed a "CNS/ATM concept", in which communications, navigation and surveillance (CNS) functions were integrated with an air traffic management (ATM) system into a global, seamless CNS/ATM system. ATM as defined by ICAO comprised not only air traffic control, but also air traffic flow management and airspace management. In a future system, controllers would function as managers of airspace, and pilots would get more responsibilities for ensuring separation and navigation. Satellite systems and digital data link were considered to be essential components of this new generation ATC system.

The CNS/ATM concept according to the FANS Committee had the following goals (OTA, 1994): With regard to *communications*, voice communication was to be replaced by automatic "data link" information exchange (in order to improve transfer accuracy and to increase capacity of the communication channels), and a global satellite system was to be introduced in conjunction with a global communications network comprising of sub-networks. With regard to *navigation*, a Global Navigation Satellite System (GNSS) had to be implemented to (gradually) replace existing line-of-sight radio navigation systems (e.g. VOR/DME). Satellite technology would allow aircraft to determine their location with high accuracy, and this position information could also be used to support reduced separation between aircraft, and to let pilots be aware of nearby aircraft in order to coordinate their flight manoeuvres.[32] With regard to

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[30] Furthermore, components of such systems, such as satellite platforms and communications networks, might be privately owned and serve non-aviation applications as well. Moreover, there were institutional issues of system ownership, operation, and control (OTA, 1994).

[31] For instance, existing line-of-sight systems had limitations in terms of propagation distance, accuracy, and reliability, and there was a lack of digital air-ground data interchange systems to support automation in airplanes and in systems on the ground.

[32] The American defence industry developed GPS (Global Positioning System) which, in the 1990s, could also be used for civil applications. The Russians developed Glosnass. In the late 1990s, the European Union developed plans for its own satellite navigation system, Galileo, to reduce dependency upon the American system.

surveillance, primary surveillance radar was to be made optional, while secondary surveillance radar was to be upgraded to Mode S in busy airspace. For less busy airspace (e.g. above oceans), "automatic dependent surveillance" (ADS), was to be implemented, using satellite communications to relay position data to ground controllers from an aircraft's on-board navigation system.[33] Some form of airborne collision avoidance also had to be implemented — with a broadcast version of ADS (ADS-B) as a main candidate. Aircraft equipped with ADS-B would send (satellite-based) position information to each other to provide surveillance and collision avoidance. The idea to let aircraft interrogate each other had already been applied in the traffic alert and collision avoidance system (TCAS) which had been a key element of the (upgraded) third and fourth generation ATC system. The difference was that TCAS was an analogue system with relatively short range, whereas ADS-B was a digital, wider-range system with a richer store of data. New surveillance technologies would make aircraft less dependent upon ground-based services and would enable pilots to safely fly their own routes.[34] Taking the concept of "area navigation" one step further, ADS-B would allow "airborne separation", making it possible to phase out the constraints of structured routes and airspace. This concept came to be known as "free flight".[35] The basic ideas behind free flight were anything but new as they had already been articulated in the 1960s.[36]

With regard to *air traffic management* (ATM) the FANS Committee concluded that handling and transfer of information had to be improved, the use of information derived from airborne systems in surveillance had to be extended, and advanced ground-based data processing systems had to be used to improve

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[33] Adam (1991) for further details on satellite systems in ATC.

[34] Automatic dependent surveillance was "automatic" because ADS needed no interrogation to elicit a response. It was "dependent" because it relied on onboard electronics rather than ground-based equipment. "Surveillance" indicated that ADS-B, coupled with GPS technololgy, could display and identify in real-time aircraft that were up to hundreds of miles aways. The pilot could be provided with position, speed and intent of surrounding aircraft relative to his/her aircraft. "Broadcast" referred to the continuous transmissions to all (Scott, 2000).

[35] Although some sort of flight plan would still be available, it would be used to assist flow management (the strategic control of air traffic), but not used as a basis for separation. "Today, pilots fly a course relayed to them by an air traffic controller and set up an airline dispatcher who designs a flight path after factoring in the weather, the fuel load of a plane, and the equipment scheduling needs of the airline. (…) Under Free Flight, a pilot would determine the flight route with approvals and guidance from air traffic controllers along the way, all the while paying attention to weather and minimum vertical and horizontal distance between planes." (Bretz, 2001: 98).

[36] An early example of a similar concept can be found in an MIT master's thesis by Bill Cotton, who is nowadays credited with the idea of free flight. "In 1965, in his MIT master's thesis, Cotton [now United Airlines' Air Traffic and Flight Systems manager] proposed that, instead of relying on ground instructions, planes could maintain flight separation through automatic air-to-air communication, with cockpit displays of the data they exchanged. At the time this scheme was a dream, since the technology to implement it didn't exist. More that three decades later, these ideas would become essential elements of the FAA's own free-flight concepts." (Scigliano, 1999: 46).

navigation accuracy in four dimensions, accommodate a flight's preferred route, and provide enhanced conflict detection and resolution.

In 1993 the CNS/ATM concept was endorsed by ICAO's member states. For the first time, a concept for a transnational ATC architecture was accepted. If each nation were to adopt it as a guiding concept in its modernisation plans, national systems could converge into a seamless global ATC system. National ATC systems were to be designed as interconnected and interoperable subsystems of a global ATC architecture. A new level of design activities emerged that focused on interoperability between, and integration of, national ATC systems. This created affordances for increased interaction and coordination. Variety in approaches to ATC system design would be reduced because of a shared guiding concept.

Since the transition toward a new "fifth generation" CNS/ATM system would require extensive coordination, the ICAO formed a Special Committee FANS Phase II to monitor and coordinate the development and transition planning for the future system. The Committee actively worked with member states to promote, explain and refine the CNS/ATM concept. In the second half of the 1990s, when architecture plans neared implementation stages, ICAO set up forums for coordination between national aviation authorities, manufacturers, air traffic controllers, and airspace users. ICAO's infrastructure enabled a comparison between the evolutions of CNS/ATM systems in different regions. In ICAO's forums recommendations could be made on issues such as interregional coordination, financing, technical cooperation and the role of each partner.

In the United States, the FAA used the CNS/ATM concept as a guiding concept in its modernisation programme "NAS Architecture". It was emphasised that the U.S. ATC system had to be designed as a part of a global architecture. Indeed, the linking of the U.S. CNS/ATM system with other CNS/ATM systems was seen as an "operationally sound and cost effective approach" for operating at the global level.[37] The FAA became a proponent of worldwide harmonisation of ATC architectures at the international level, not only because this would enhance safety and efficiency of air traffic, but also because it would reduce international regulatory costs to industry through harmonisation, regulatory cooperation, and joint research, development, and implementation of new technologies. American industry could be expected to benefit as technology transfer to other countries which had adopted the CNS/ATM concept would become less difficult.[38] The FAA worked with ICAO's regional planning and implementation groups and exchanged information with these groups.[39]

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[37] NAS Architecture newsletter, nr.3, September 30, 1996.

[38] NAS Architecture newsletter, nr. 3, September 30, 1996.

[39] NAS Architecture newsletter, nr. 13, February 10, 1998.

Alignments with other ATC actors were necessary to design and implement the NAS Architecture. The FAA used a variety of methods to create such alignments: it hosted delegations of aviation representatives from other nations, it participated in international aviation workshops, conferences and airshows, and it provided NAS Architecture briefings and drafted ICAO information papers. In addition to being a roadmap for modernisation of the U.S. ATC system, the NAS Architecture programme also served as a foundation on which the FAA could base its collaboration with the international community to ensure a smooth operating global aviation system.[40]

The FAA and Eurocontrol increased their coordination and collaboration as they recognised that a next generation ATC system had to be an internationally interconnected and coordinated architecture. Already in 1986, the FAA and Eurocontrol had signed their first Memorandum of Cooperation (to be implemented through annexes),[41] which was revised in 1992. The agreement had provided for the exchange of information with regard to programmes, projects, research results and publications, the execution of joint analyses, the exchange of scientific and technical personnel, the coordination of R&D programmes and projects, the exchange and/or purchase of specific equipment and systems for research activities and compatibility studies, and the joint organisation of symposia or conferences. International cooperation was also used to reduce costs for civil aviation authorities (which were facing shrinking resources to upgrade and develop their ATC systems) as well as ATC users (which could avoid dual equipage costs and profit from seamless, "gate-to-gate" global air travel). The FAA and Eurocontrol became part of a network of organisations and forums promoting international collaboration and coordination in R&D, specification of procedures, and processes aimed at global harmonisation and interoperability. In 1997, they formed an Architecture Collaboration Group to advance the study of global CNS/ATM architectures and lay the foundation for future international compatibility. The aim of these collaborations was to develop a common understanding of their architectures, and to develop a collective "big picture" perspective and strategy. A proposal was developed to reach worldwide cooperation to support a standard global CNS/ATM architecture.[42] During 1998 a start was made in assessing and comparing respective CNS/ATM systems in the United States and Europe. To ensure progress toward a harmonised

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[40] NAS Architecture newsletter, nr. 13, February 10, 1998.

[41] Twelve annexes were signed, including: Radar Analysis Support System; Data Link and Transponder Analysis System; Advanced ATC Automation requirements; ATM and Flight Management Systems Integration; Automated En Route ATC (AREA) — Advanced Research in ATC (ARC); Meteorological Forecasting; Aeronautical Telecommunications Network (ATN); ATM Simulation Modelling and associated activities; Global Navigation Satellite System (GNSS); Coordinate Infrastructure; Digital Aeronautical Voice Telecommunication Network; Development of ATM Procedures.

[42] NAS Architecture newsletter, nr. 13, February 10, 1998.

architecture, a collaborative framework for the involvement of aviation technical expertise was planned.[43]

With regard to its activities on an architectural level, and the production of architectural knowledge, the FAA was supported by a number of intermediary actors, including RTCA, SETA (System Engineering and Technical Assistance), and, in particular, MITRE's Center for Advanced Aviation Systems Development (CAASD).[44] In 1990, MITRE had been asked to incorporate CAASD as a Federally Funded Research and Development Center (FFRDC). In general, FFRDCs assist the U.S. government with scientific research and analysis, systems development, and systems acquisition.[45] Their aim is to solve complex technical problems by bringing together the expertise and outlook of government, industry, and academia. FFRDCs work in the public interest, and are organised as independent, not-for-profit entities, with limitations and restrictions on their activities — they are, for instance, prohibited from manufacturing products or competing with industry, which make them trustworthy partners for industrial parties. They operate as strategic partners with their sponsoring government agencies, and provide guidance across the full spectrum of capabilities development, from planning and concept design to technology insertion and integration. As a FFRDC, MITRE/CAASD was a prominent consultant for the FAA, and supported the FAA in developing and assessing new technologies, and in formulating new programmes. MITRE/CAASD came to play an important role in the production and dissemination of technological knowledge about ATC architecture design and implementation.

The intermediary actor RTCA welcomed the integrated, satellite-based ICAO CNS/ATM concept and became a champion of Free Flight. The RTCA regarded the existing ATC system as outdated and inefficient because the technologies which made up the ATC system had been developed independently and at different times, and were not necessarily designed to work together.[46] It was considered "remarkable that it work[ed] as well as it [did], given the way it

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[43] Additional FAA-Eurocontrol collaborative R&D activities included airborne separation concepts; air traffic operational concepts; air traffic modelling, simulation and analysis; evolution of the air traffic system architecture; validation and certification methodology; ATM decision support tools; and ATC procedures.

[44] CAASD has technical capabilities in operations research, computer science, electronic and systems engineering, and in-depth domain knowledge in behavioral science, human performance and ATM. In addition, CAASD provides highly specialised simulation and computer modelling capabilities and facilities to model improvements across a broad spectrum of NAS systems and operations.

[45] FFRDCs currently number more than 40 different organisations, and work in the fields of defence, energy, aviation, space, health and human services, and tax administration. All FFRDCs are sponsored by government agencies, but are privately administered by universities and other not-for-profit organisations ("What is an FFRDS?" at website of MITRE).

[46] RTCA diagnosed the ATC system as a rigid and largely procedural, analogue, and ground-based system comprising HF/VHF-voice communications, terrestrial-based navigation systems, radar surveillance, and limited air traffic decision support.

[had] grown. For 40 years, functions, hardware and software [had] been mixed, matched, replaced and added in, forming a massive patchwork." (Scigliano, 1999: 46). RTCA was part of a lobby to convince Congress that Free Flight would invoke cost reductions. Congress deputed RTCA "to draw the map to free flight" (Scigliano, 1999: 47). A RTCA Task Force had to bring some order in the debate by developing an acceptable definition for Free Flight.[47] To guide implementation of free flight, the RTCA Task Force 3 "Free Flight Implementation" was formed. In 1995 the Task Force published its report as an input in the NAS Architecture plan (RTCA, 1995).

Designing a next generation architecture was as highly politicised process which involved many deliberations and negotiations. Budgetary limits and (vested) interests of various stakeholders, such as commercial and military airspace users, aviation manufacturers, and air traffic controllers had to be taken into account.[48] The NAS Architecture was to provide a defensible basis for FAA's investment decisions and to reduce uncertainties for the aviation industry in its attempts to prepare long-range plans.[49] Within the United States, the NAS Architecture was discussed in conferences, symposia and workshops of intermediary organisations like ATCA and RTCA, and it was communicated through a set of documents, briefings, speeches, workshops, and the FAA homepage. The NAS Architecture functioned as roadmap that showed the "where, how, and when" of NAS evolution.

The NAS Architecture plan was finally approved in 1999 by the FAA, after several versions had been released in the second half of the 1990s. The NAS Architecture was to be implemented in three phases. In the first phase (1998-2002), existing NAS systems and services were to be maintained while new systems such as the standard terminal automation replacement system (STARS), display system replacement (DSR), satellite augmentation systems,[50] and air-to-air surveillance were to be introduced.[51] During the second phase (2003-2007),

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[47] Free flight was eventually defined by RTCA as "a safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a step towards free flight...." (RTCA, 1995).

[48] Actors which were briefed and consulted included several FAA offices, the General Accounting Office (GAO), the Aircraft Owners and Pilots Association (AOPA), the Air Transport Association (ATA), the Air Line Pilots Association (ALPA), the Air Navigation Commission of ICAO, the National Business Aviation Association, the Air Traffic Control Association (ATCA), the Radio Technical Commission for Aeronautics (RTCA), Airport Council International Technical Committee, and Department of Defence (DoD) representatives.

[49] NAS Architecture newsletter, vol. 1, nr. 1, July 31, 1996.

[50] With augmentation systems GPS information could be made more precise and accurate.

[51] NAS Architecture newsletter, nr. 21, March 11, 1999.

new CNS technologies were to be deployed, and satellite augmentation was to completed to provide extended coverage and precision instrument approaches.[52] Automatic dependent surveillance (ADS) ground equipment was to be installed to extend ATC surveillance services to non-radar areas, e.g. above oceans.[53] At the same time, aircraft were to be equipped with automatic dependent surveillance-broadcast (ADS-B) avionics to enable airborne separation. During the third, and final, phase (2008-2015) the required infrastructure and integration of CNS technologies were to be completed.[54] Part of the future NAS Architecture was a systemwide computer network with standardised data formats which would enable controllers and pilots to receive and share common information to enable joint decision-making. To that end, the existing array of independent systems and varying standards had to be replaced by a shared environment which connected pilots and controllers for traffic flow management, flight service, and aviation weather information.[55]

In Europe, Eurocontrol was a champion of a seamless European CNS/ATM infrastructure. While Eurocontrol had been founded in 1960 with the (modest) objective to oversee ATC in the upper airspace of the Member States of the European Civil Aviation Conference (ECAC), it became an transnational actor with the mission to development a coherent and coordinated European ATC system. The European airspace was even more congested than in the United States. Within Europe, there were 31 national ATC systems (with more than 60 centres) that divided European airspace along national lines. This resulted in a lot of air time being spent on "handing over" flights from one to another (Anonymous, 2001). European nations had built up their own ATC infrastructures, and the resulting broad technical diversity in infrastructure made ATC across borders difficult and inefficient. To achieve an integrated European system, Eurocontrol developed the European ATC Harmonisation and Integra-

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[52] During the second phase, software applications of DSR and STARS were to be recoded and new applications were to be added to support ATC functions.

[53] NAS Architecture newsletter, nr. 21, March 11, 1999.

[54] During the third phase, the hardware and software of DSR and STARS were to be improved to accommodate advanced controller tools such as conformance monitoring, conflict detection, and enhanced arrival/departure sequencing. These tools were to enable controllers to maintain clear weather aircraft-acceptance rates at airports during inclement weather conditions.

[55] Illustrative of the intended systems integration were the weather services. The FAA planned to integrate the existing NAS stand alone weather systems into a weather server so that information would become single-source and shared by all systems. Weather information (gathered and processed at the servers) was to be made available to pilots, controllers and other stakeholders in a timely manner. This would promote common situational awareness and would enhance collaborative decision making for controllers, traffic managers, aircrews, and dispatchers (NAS Architecture newsletter, nr. 21, March 11, 1999).

tion Programme (EATCHIP) in 1990 as a framework of top-down change within which national and international plans could be developed.[56]

In the late-1990s, when air traffic delays reached unprecedented levels, EATCHIP was succeeded by the European ATM Programme (EATMP) to implement the "ATM Strategy 2000+" which had been approved by European Transport Ministers. This ATM Strategy 2000+ aimed to create a single European airspace and to increase the capacity of the European ATM system by a renewed harmonisation and integration effort.[57] EATMP spanned several domains, including programmes for the development and implementation of an airborne collision avoidance system, for the coordinated implementation of data link (Link 2000+), and for a harmonised and coordinated approach to the development and implementation of a global navigation satellite system.[58]

With regard to knowledge production, Eurocontrol drew up European R&D programmes in which European organisations could collaborate. The Eurocontrol Experimental Centre also played a central role in European research and development. An early example of research collaboration was the Programme for Harmonised ATM Research in Eurocontrol (PHARE), which started in 1989 and was completed in 1999.[59] The purpose was to investigate an advanced ATM concept, similar to Free Flight. In the planning and execution of PHARE, a number of European research centres, assisted by national authorities, combined their ATC and aeronautics experience and resources to mount a comprehensive and coordinated research effort, building on existing in-house programmes. Thus, with its various research and development programmes, Eurocontrol contributed to consolidation of ATC knowledge in Europe. National variety in approaches to ATC architecture design and implementation diminished. Instead, an international approach emerged, guided by a shared CNS/ATM concept.

While ATC architectures increasingly became a part of a global architecture, the ATM industry witnessed a process of concentration and consolidation. Ties between national governments and domestic industries became less tight. After a series of mergers and take-overs, only a few large multinational players

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[56] In the first phase of EATCHIP, the existing situation was assessed in order to obtain, for the first time, a complete picture of the European ATC services, systems and procedures. In the second phase, the deficiencies and problems identified in the first phase were addressed. As a result, two complementary programmes were established; the EATCHIP Work Programme and the Convergence and Implementation Programme (CIP). In the final phase, an integrated European ATM system, conform ICAO's CNS/ATM guiding concept, had to be implemented.

[57] For details on ATM Strategy 2000+ see website of Eurocontrol

[58] Other programmes included European Aeronautical Information Services Database and Reduced Vertical Separation Minimum.

[59] For details on PHARE see website of Eurocontrol.

remained in the late 1990s. The most important companies were Raytheon, Lockheed Martin, Northrop-Grumman, Airsys ATM, and Alenia Marconi (Bourrez, 2000).[60] These companies could profit from the fact that national governments wanted to implement systems which were compatible with a global CNS/ATM architecture. They became globally active and began to offer complete turn-key CNS/ATM systems.[61] Thus, technological solutions were developed which were general enough to be implemented in different countries.[62] Remarkably, Boeing also became active in the ATM market. As an aircraft manufacturer, Boeing had a direct interest in solving the problem of congestion and delays in the airspace system. It used its expertise in systems engineering to develop a ATM concept which was compatible with ICOA's CNS/ATM concept.

While the implementation of the "fifth generation" ATC system is still underway, it can be concluded that the approach to ATC systems design had changed significantly since the Second World War. Nowadays, ATC systems are designed as interconnected architectures in which each subsystem is taken as an interoperable part of a large whole. Such an architectural approach was first introduced on a national level when systems engineering companies such as MITRE and MIT Lincoln Lab became heavily involved in the design and implementation of the ATC architecture. Since the 1980s, when the CNS/ATM concept became a shared guiding principle, international coordination and collaboration have become much more prominent. The ICAO played a stimulating and coordinating role at a transnational level. In Europe, Eurocontrol became

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[60] Raytheon was the largest player in the American market, with Lockheed Martin and Northrop-Grumman as its main American competitors. Raytheon/Indra and Lockheed Martin increasingly became active in the European market during the 1990s. Airsys ATM was the result of a merging of the ATM activities of Thomson-CSF (which also included Hollandse Signaal Apparaten), Plessey, Siemens and Alcatel. Alenia Marconi was the result of merging of ATM activities of Alenia and Marconi. "[The] American Industry has a roughly 30% market share in Europe, while European industry has no access to the U.S. market. However, European industry is flying the European flag in the rest of the world with a majority share of the accessible market." (Bourrez, 2000: 43).

[61] Illustrative is an advertisement text by Raytheon "From Australia to the USA, India to the United Kingdom, Canada to China, Norway to Oman, Raytheon is delivering the very latest technology and full-featured air traffic management systems. From the design, production and installation of a single radar or automation system, to the nation-wide integration of a total air traffic management system, Raytheon is your partner. We handle all aspects of system integration including provision of data and voice communication, satellite navigation systems, surveillance systems (primary, secondary, radar, ADS), landing systems and ATM for total CNS/ATM solutions. As a proven contractor Raytheon delivers full turnkey CNS/ATM service including planning, design, procurement, implementation, transition, training and long-term organizational support." (Website Raytheon).

[62] Raytheon developed the "AutoTrac" system, Lockheed Martin the "Solution 21", and Airsys the "Eurocat 2000" system. Raytheon was awarded contracts by the United States, Norway, Germany, Australia, India, Oman, Hong Kong, China, the Netherlands, and Lebanon. Lockheed Martin delivered (sub)systems to the United Kingdom, Belgium, China, the Czech Republic, Germany, Hong Kong, India, Indonesia, Singapore, Taiwan, and others.

increasingly involved in the design and implementation of an integrated European CNS/ATM architecture.

7.3 In conclusion

The case study of ATC was selected as an extreme case to examine whether my conceptualisation of cosmopolitanisation would also be valid for complex systems in the top of the technological hierarchy. First I will summarise the successive generations which structured the case study. Then I will examine what can be seen in terms of cosmopolitanisation.

Table 7.1 Generations in ATC systems

Generation	*Typical elements*
First generation (1920s-1930s)	manually operated, procedural indirect radio for communications airways marked by visual and low frequency radio range navigation aids first en route ATC units
Second generation (1940s-1960s)	primary surveillance radar at airports and en route centres direct (UHF/VHF) communications airways marked by VOR/DME navigation aids Instrument landing system introduction of jet aircraft
Third generation (1960s-1980s)	positive control in designated segments of airspace semi-automated ATC system (NAS En Route Stage A & ARTS) secondary surveillance radar upgraded secondary surveillance radar (discrete addressing)
Fourth generation (1980s-2000s)	Mode S data link (digital) TCAS for collision avoidance area navigation new landing aids Advanced Automation System (failed)
Fifth generation (2000s—)	CNS/ATM concept satellites for communications, separation and navigation Automatic Dependent Surveillance (ADS) airborne separation (ADS-B) Free Flight air traffic management (rather than air traffic control)

Every generation was configured around the type of aircraft and the volume of air traffic of its age. Especially the introduction of jet aircraft had a major impact on the design of ATC systems. With each generation complexity and interconnectedness increased. Humanware was increasingly replaced by hard- and software. Systems for communication, navigation and surveillance were increasingly integrated. This made modernisation an increasingly complicated undertaking which called for a planned and coordinated approach. On a national level, the ATC system was increasingly designed as an (open) architecture of interoperable subsystems, rather than as a loosely coupled network of systems which was characteristic for the early generations. With each generation international interoperability became more important. Recently, ATC systems are designed as parts of a global ATC architecture based on ICAO's CNS/ATM concept. In Europe, for instance, harmonisation and integration of national ATC systems is underway.

Before the Second World War, ATC was a loosely coupled socio-technical system which was largely a procedural and manually operated. Local control units at airports and en route control centres and pilots had considerable autonomy. Knowledge production at the level of the overall architecture was limited, ad hoc and reactive. After the war, the ATC system rapidly grew more complex. New communications systems, radar and display systems and new navigation and landing systems were introduced which induced a more coordinated approach to the design of the overall system. Because of the international nature of air traffic, international standards were established to ensure compatibility between technologies on the ground and between aircraft. This phase can be characterised as an "inter-local" phase, in which ATC technological developments were shaped by anticipations on international standardisation. While national aviation authorities recognised that they were interdependent, they followed their own national approaches to ATC system design and implementation. Standardisation occurred on the level of subsystems, rather than the overall architecture. American navigation and landing aids were selected as standards, and became standard elements in ATC systems worldwide. The automation projects of the 1960s and 1970s are a clear example of nations developing their own idiosyncratic technological solutions without much coordination. In response to capacity and safety problems, ATC systems grew more complex and interconnected as new subsystems were added (e.g. data link and collision avoidance systems). Modernisation became increasingly difficult because interoperability had to be guaranteed: old and new generation systems had to interoperate during transition; new systems had to fit into an existing architecture; and interoperability with an international air fleet had to be created. In anticipation on ICAO standardisation, national ATC actors exchanged information on their plans and objectives in an effort reduce the risk that another incompatible system would become the standard. As the ATC system grew more complex, inertia increased. During the 1980s automation projects in the U.S. became an expensive failure as it proved very difficult to "rehost" computers with new software. This increased complexity induced the FAA to adopt a more systematic and planned approach to modernisation of its ATC system. Intermediary organisations like MITRE and MIT Lincoln Lab were contracted to provide technological and managerial assistance. Actors involved in design and implementation of ATC systems were increasingly reflexive about the architectural nature of the ATC system, in which each element had to be designed as an interoperable part of the overall architecture.

During the 1980s, a "trans-local" phase emerged which was partly the result of projections of a substantial increase in air traffic which could not be dealt with with existing systems. Within the transnational organisation ICAO, the

CNS/ATM concept was created which could serve as a guiding principle in the development of national ATC systems. With the adoption of the CNS/ATM concept, national approaches to ATC system design and implementation could be coordinated. National ATC systems came to be seen as interoperable elements in a global ATC architecture. Activities on a transnational level increased significantly. In Europe, the transnational organisation Eurocontrol became a sponsor of harmonisation and integration of European ATC systems. International collaborations increased. The research centres of the FAA and Eurocontrol, for instance, collaborated and kept each other informed on the outcomes of their research activities. As the ATM industry concentrated in the 1980s and 1990s only a few large (multinational) companies remained active in the design, implementation and integration of ATC systems.

Contemporary ATC system development has become an internationally coordinated undertaking. Large parts of knowledge on ATC system development are shared, including general guiding principles and notions of what the basic elements of an ATC architecture should be. There are many standards with regard to data formats, and interfaces. The shared basic concepts shape the actual design and implementation projects which indicates that a reversal has taken place. While knowledge on the architecture level is cosmopolitanised, the actual design and implementation require much accumulated expertise which is not collectively available. Extensive knowledge of the contexts in which new systems have to be embedded remain necessary — if only because backward compatibility has to be taken into account. Interestingly, large companies like Raytheon have developed expertise to design and implement ATC systems anywhere in the world which can be labelled as "auxiliary aggregation" since it enables a systematic application of cosmopolitan architectural knowledge.

What this case study has shown is that cosmopolitanisation coincided with the development towards a global ATC system. In this process, socio-political processes of deliberation and negotiation and socio-cognitive processes of developing decontextualised design concepts were interwoven. National styles in ATC architecture design and implementation have converged, and activities on the architecture level are increasingly guided by shared repertoire of concepts and solutions. This allows for an anticipatory, planned and internationally coordinated approach.

Technological affordances

Complexity created a dual affordance structure. On the one hand, complexity means that ATC system are multi-location and multi-actor systems which require alignments between a heterogeneous set of actors. To ensure a reliable performance, a robust understanding of the system is required. On the other hand, complexity means that the production of translocal knowledge is difficult because of the uniqueness of ATC systems. As the ATC architecture grew more complex, the management of alignments between actors and locations proved to be an increasingly complex task. Committees of experts were periodically established to draw up recommendations, based on a study of various interests and technological options. Systems engineering organisations like MITRE came to play an important role to manage the integration of various projects into one coherent whole. The translocality that was achieved, however, was geared to a specific ATC configuration — although MITRE succeeded in using its expertise in countries outside the United States as well.

Because of the systemicness, the development of ATC systems was characterised by a generational dynamic. As the elements of the ATC architecture became increasingly interconnected with each generation, the overall performance of the next generation could only be guaranteed if all elements were taken into account simultaneously. This created affordances for a systematic, integral approach to ATC systems design. The high level of complexity made it difficult to experiment with several alternative solutions. Instead, new systems had to be carefully specified and tested before they could be implemented. This is also related to the high level of risk involved: failure could have catastrophic consequences. This created affordances to reduce uncertainties beforehand, by modelling, prototyping and simulation, and to follow an incremental approach based on proven technologies (and off-the-shelf equipment). The high level of complexity and systemicness also made it difficult to change the overall configuration. Once this was recognised as a problem, it created affordances for a systematic and programmatic approach to modernisation projects. Nowadays, the design and implementation of ATC systems is negotiated *ex-ante* which is only possible if designs are articulated. Whereas the first generations were developed by coupling of available technologies taking into account the historically evolved situation, this approach were replace by architectural design according to internationally accepted guiding concepts, which had to be filled in with technologies.[63]

Interoperability played different roles: interoperability between subsystems, interoperability between ground-based and airborne equipment, backward and forward interoperability, and, finally, interoperability between national ATC systems. Such requirements create a high level of affordances. Especially when

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[63] Braun and Joerges (1994) make an interesting distinction between first-order and second-order large technical systems (LTS). "First-order large technical systems refer to the familiar, relatively easily delimited all-purpose infrastructures such as the road, railroad, energy, and telecommunication systems that have been at the center of large technical systems research. By contrast, the concept of second-order large technical systems refers to the process of networking parts of different first-order systems for specific, macro-level social domains (). Much of today's large technical systems' expansion and transformation can be interpreted as superimposing second-order large technical systems on more or less stabilized classic infrastructural systems." (27).
Historically, first-order LTSs have been built up in "a rather erratic though clearly expansive, bottom-up way." (35). LTSs begin in different local centres for demonstration and experimentation. Step-by-step, these are linked up to regional networks, which in turn are integrated into national and international infrastructural systems. The growth of the system coincides with the growth of controlling organizations. In second-order LTSs the dynamic is not bottom-up but top-down. A key difference is that they do not have to start from scratch. The growth of second-order LTSs is characterized by adding of subsystems. "The development of a global CNS/ATM architecture can be understood in terms of a second-order LTSs which builds on existing systems and infrastructures. The transition from a bottom-up to a top-down approach was clearly visible in the case of ATC.

the control philosophy shifted and pilots were given more responsibilities, interoperability became vitally important.

In sum, technological affordances create a mixed affordance structure: on the one hand there were affordances to produce reliable and translocal knowledge (to deal with complexity and uncertainty) and on the other hand the heterogeneous and unique nature of the technological configuration made it very difficult to produce configuration-transcending knowledge. Much of the knowledge production centred around attempts to increase reliability and efficiency of one particular system, rather than a class of systems.[64]

Megamachine dynamics were clearly present in the ATC case. Increasingly, design and implementation activities became disciplined by requirements defined at the level of the overall architecture, first on a national level, and since the 1990s on a transnational level. ATC system development became a complex coordinated megamachine. In the megamachine, technology and actor constellation were interwoven. The central role of national aviation authorities, for example, reinforced the megamachine.

Actor constellation affordance

The case of ATC was a clear example of a mission-oriented innovation pattern, in which governmental actors played a dominant role as clients. In the United States, the mission-actor FAA was responsible for an efficient and safe ATC system. Under its authority modernisation plans were developed and implemented. FAA's Experimental Centre (NAFEC) played an important role in the production, testing and certification of ATC technologies. Other important knowledge producers were research organisations like MIT Lincoln Lab and MITRE. Large high-tech companies like IBM, Raytheon, and Lockheed Martin were also part of a division of labour.

The presence of the dominant mission-actor FAA created an affordance for the production of robust knowledge on the ATC architecture. The FAA was responsible for safe air travel, and required reliability. With the FAA as the sole client, there was a monopsonistic market in which the FAA could award contracts to contractors with the "best" design. Only certified technologies were allowed to be used in the ATC system and onboard aircraft.

On an international level aviation authorities were interdependent. They had to ensure that aircraft flying from one country to another could interoperate with ground-based equipment in different countries. When interdependen-

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[64] This is in line with Stankiewicz (2000) claim that "even though the design spaces of architectural regimes are typically vast and ill defined, there are strong pressures to articulate and standardize them." Stankiewicz presents a classification of craft, engineering, architectural, and research regimes. A difference between architecture design and 'classical' engineering design is that functional requirements cannot be taken as exogenous givens. Complex architectures are few in number and often unique. Conventional trial-and-error is generally out of the question. Architectural knowledge is like craft knowledge, in that it is harder to define, accumulate and communicate than engineering knowledge. Generally, there is a large tacit dimension and a high degree of 'subjectivity' (e.g. 'design philosophies' & 'schools of thought').

cies increased because of an increase in international air traffic, this created affordances to coordinate and exchange intentions and plans. In Europe, the establishment of Eurocontrol can be understood as a result of increased interdependencies. Eventually, the transnational ICAO took the initiative to develop a general CNS/ATM concept as a guiding principle for national aviation authorities to enable coordination and collaboration.

An interesting aspect in the case of ATC was that there were many actors involved: aircraft owners, pilots, airlines, controllers, all lobbied for their interests which were often conflicting. The production of translocal knowledge at the level of the architecture was shaped by socio-political processes and efforts to create alignments. To what extent did the heterogeneity of the actor constellation create affordances for cosmopolitanisation? The need to justify design and implementation decisions created an affordance to create ATC architectures which could be convincingly defended against critics. In the 1990s, the FAA would make sure that in the development of the next generation ATC architecture all stakeholders could have their say. Thus, the need to create acceptability, created an affordance to create architectures which could be backed up with robust knowledge and reference to internationally shared design concepts (such as ICAO's CNS/ATM concept).

For knowledge producers like MITRE, MIT Lincoln Labs and industrial parties, it was important to build up a good reputation. This created affordance to be active on a cosmopolitan level and participate in conferences, committees, and other forums.

Secular changes affordance

ATC system development began in the 1920s and continues today. Relevant secular changes were the central role of the nation state in the development and maintenance of national ATC systems. Recently, privatisation and liberalisation are important secular changes which affect ATC system development: private companies are increasingly allowed to provide ATC services, and national markets have opened up for an internationalised ATM industry. The harmonisation and integration of European ATC systems is part of a broader economic-political European integration process.

The dynamics were also shaped by the Cold War and the emphasis on national security and sovereignty in national airspaces. Much of the technologies employed in civil ATC systems were developed in the military domain. The emergence of satellite technology and worldwide communication networks made it possible to conceive ATC as a worldwide seamless system. Recently, a shift towards "postmodern technology and management" (Hughes, 1998) was visible when open architectures, and distributed control ('Free Flight') were promoted.

Chapter 8.
Conclusions

8.1 Introduction

In this chapter I will collate findings from the four case studies and see if, and how, they add up to a more robust understanding of cosmopolitanisation processes. My point of departure was that sharing of technological knowledge was not obvious because technological knowledge is local in origin local and needs to be decontextualised to become shareable. Moreover, the emergence of a collective knowledge reservoir, which characterises technological regimes, is a collective good, and the production of collective goods is not self-evident. My research questions were: how can sharing of technological knowledge, the essential step towards the emergence of a technological regime, occur? And when it occurs, can we understand why, and how it will be shaped? In Chapter 2, I presented a conceptual model in which I specified the phenomenon of cosmopolitanisation as a sociocognitive structuration process in which technological knowledge is made translocal through circulation and aggregation, supported by an (evolving) infrastructure and situated in an (evolving) division of cognitive labour. Characteristic of this division of labour is the emergence of a cosmopolitan level of knowledge activities which centres on the production, maintenance, improvement and distribution of a collective knowledge reservoir.

The second part of my conceptualisation was the specification of an affordance structure to understand cosmopolitanisation dynamics. Constituent parts of this affordance structure were technological aspects, the actor constellation, and the presence of existing mosaics of technological regimes and the historical setting (the socio-technical landscape). I argued that there was no simple causality, but that affordances were interdependent, dynamic and co-evolved with ongoing cosmopolitanisation. Elements in the affordance structure could not be studied as a set of separate hypotheses, given their interrelated and dynamic nature. Instead, the four case studies were used as trials of strength in which it was studied whether (dynamics in) the overall affordance structure could account for patterns in cosmopolitanisation. Each case was selected to create a contrast with the previous case(s).

In the next section, I will first summarise and discuss cosmopolitanisation patterns which were identified in the four case studies (sections 8.2.1—8.2.4). In comparisons between different cases I will already make some analytical points. Then, in section 8.2.5, I will discuss differences and similarities in findings from the case studies. I will present a general pattern of cosmopolitanisation. In section 8.2.6 I will discuss and draw conclusions about technology affordances, actor-constellation affordances, and secular changes. Finally, in section 8.3 the findings of this study are discussed and some implications are presented.

8.2 Findings from the case studies

8.2.1 Cosmopolitanisation of reinforced-concrete technology

Cosmopolitanisation of reinforced-concrete technology occurred in a pattern of four phases: a local phase, an inter-local phase, a trans-local phase and a cosmopolitan phase. In the first, local phase (1850s—1870s), various innovative actors made new combinations of iron and concrete to solve specific problems some of them developed it into a construction technology. There was "success without understanding" within local practices while applications of reinforced concrete were limited to several niches. Knowledge was experiential, based on accumulated experiences and trial and error learning within local practices. It remained local, and producers were secretive.

In the second, inter-local phase (1870s—1890s) applications of reinforced concrete increased and producers developed proprietary "systems". Entrepreneurial contractors developed networks of licensees in which knowledge circulated and was shared. A battle of patented systems occurred while it was difficult for customers to assess the merits of the systems. Customers became increasingly interested in the new material. To increase their markets, reinforced-concrete contractors tried to convince customers and inspectorates by disclosing parts of their knowledge and methods, thereby using forums of engineering societies and the building trade. Reliability and durability were main issues for customers, and they could not be established by tests of finished structures alone. The risk of collapse needed to be reduced not just by tests of finished structures, but also by systematically generated experimental data and theoretical insights which allowed for calculations of strength. In journals and elsewhere debates emerged in which reliability and durability of various systems was discussed by proponents and sceptics. Contractors as well as demanding customers increasingly became involved in a theoretical-experimental effort in which the performance of (systems of) reinforced concrete could be explained and predicted. This was the beginning of a local-cosmopolitan division of labour and the emergence of a cosmopolitan level supported by infrastructure of the civil engineering community.

The third, trans-local phase (late-1890s—1910s) was characterised by standardisation of reinforced concrete. As long as collapses could be attributed to inherent flaws in the technology, reinforced concrete would not be widely accepted. At the initiative of dominant, demanding customers and inspectorates, and supported by leading contractors acting out of enlightened self-interest, committees of experts were established to create standards based on translocal knowledge, i.e. experimentally validated theoretical knowledge rather than practical empirical rules related to experiences with specific systems. Contractors and consulting engineers published handbooks in which knowledge was disclosed. In technical journals articles on reinforced concrete were published to show that reinforced concrete was reliable and calculable. New specialist journals emerged which supported further cosmopolitanisation. Reinforced concrete was taken up in curricula of polytechnics and technical universities. With the emergence of associations like the German *Beton-Verein*, the local-cosmopolitan division of labour became more elaborate. Reinforced-concrete knowledge became increasingly institutionalised and a collective knowledge reservoir was built up. At the end of the 1910s, the cosmopolitan level started to get a dynamic of its own, carried by an increasingly elaborate infrastructure.

In the fourth, cosmopolitan phase (1920s—), a reversal occurred in which a normal practice emerged, guided by cosmopolitan knowledge which was incorporated in standards, rules for calculation, handbooks, curricula, etc. Technical societies were established which became active in collaborative research and standardisation activities. After the Second World War, cosmopolitanisation was further increased as new intermediary actors (e.g. the CUR) were established to promote collaborative research and sharing of knowledge. By then, reinforced concrete was something that any contractor of any significance had to be able to apply.

This phased pattern in cosmopolitanisation could be explained by co-evolving and increasing affordance structures. The affordance structure in the first phase was low. For local practices there was an affordance to learn from experiences because of the repeated nature of design and production, but there were few affordances to produce translocal knowledge because the level of complexity was low and application of reinforced concrete was largely limited to relatively simple artefacts. The actor constellation was characterised by an absence of dominating or demanding actors. In the second phase the affordance structure increased as reinforced concrete was increasingly applied in more complex structures and buildings. Both technological and actor-constellation affordances increased. The enigmatic nature of reinforced concrete became a challenge for contractors as well as professional customers and inspectorates. The risk involved in larger structures induced efforts to reduce or control variabilities in materials and execution methods, and to reduce risks and uncertainties before actual construction by making reinforced concrete calculable and underpinning it with engineering theory. Interdependencies between contractors competing with alternative systems increased, especially when demanding customers and inspectorates began to produce knowledge on reinforced concrete as such, rather than on specific systems. In the third phase, a threshold for collective action was overcome when standardisation committees were established by Ministries for Public Works and professional engineering societies. Standards were recognised as a collective good which would both benefit contractors as well as customers — although contractors had reservations about translocal knowledge and maintained that a good constructional sense remained important. With the establishment of trade associations and technical societies, the actor-constellation affordance increased as it co-evolved with further cosmopolitanisation.

Secular changes influenced cosmopolitanisation. The case clearly showed the prominent role of professionalised civil engineers with their societies, forums, and esprit de corps in the 'rationalisation' of reinforced-concrete technology. Also the uptake of reinforced concrete in curricula of technical universities was part of such professionalisation and emerge of "school culture". The increasing role of the nation state in science and technology also affected cosmopolitanisation. For instance, the establishment of subsidised sectoral research centres helped to overcome thresholds in collective action, which was of particular importance because the industry structure was characterised by many small contractors.

8.2.2 Cosmopolitanisation of paint technology

While paint is also on the level of materials in the technical hierarchy, cosmopolitanisation was much slower and less substantial than in the case of reinforced concrete. Nevertheless, a similar phased pattern could be identified, which indicates that the phases might be general, although they can be lengthened, shortened, or modified.

A local phase, without much cosmopolitanisation, lasted until the 1910s. Knowledge on paint formulation was experiential knowledge, based on years of experience in local practices. Circulation was limited, although there were experts who travelled around and wrote handbooks in which they gave guiding recipes. Paint formulation was surrounded by secrecy, and paint knowledge was learnt on-the-job. As in the early phase of reinforced concrete, the affordance structure was low. Technological affordances for production of translocal knowledge were limited. Although the repetitive nature of paint formulation created affordances to learn from experiences, such experiential knowledge remained tied to local contexts and specific formulation practices. The level of complexity was low and there were few risks or uncertainties which needed to be reduced. Unlike reinforced concrete, paint does not play a constructive role in higher-level configurations. The actor constellation consisted of many small regionally active paint formulators, suppliers of paint ingredients (which were producers of knowledge on the level of ingredients), and customers which were not dominant nor demanding. Trust was created in bilateral trading relations, and customers did not need to be convinced by disclosing paint formulation knowledge. Around 1900, affordances started to increase as paint formulators began to use mechanical apparatus for grinding and mixing which improved controllability of the formulation process. Suppliers introduced upgraded materials with more uniform and predictable qualities which improved controllability of paint formulation. At the same time, large industrial customers emerged which demanded paints with uniform, repeatable and higher performances. They were dominant, but not demanding in terms of how the performance was achieved. Standardised test methods to assess the performance were developed to regulate trading relations. Paint companies established (small) laboratories for testing and quality control. Formulation knowledge remained empirical, and circulation remained limited.

After the First World War, an inter-local phase emerged which was characterised by increased knowledge production. When paint manufacturers established a trade organisation, this provided a means to overcome thresholds in collective action in a sector characterised by many small manufacturers. When new/upgraded chemical ingredients were made available, trade associations began to play a role in studies on how to use these new materials in paint formulation. In the UK, the Paint Research Association was established which became part of an emergent local-cosmopolitan division of labour. The establishment of this association was part of secular changes in which nation states become more actively involved in promotion of (collective) industrial R&D. In the 1950s and 1960s, collective knowledge production increased as new research associations and professional societies were established and governments stimulated collective industrial research. Courses were developed by industry associations to promote professionalisation of paint technologists. The technology affordance increased as formulation practices become more controllable and measurable with the introduction of synthetic ingredients and instrumentation. The paint industry remained dependent upon suppliers in the chemical industry who provided them with guiding recipes for new synthetic ingredients. The actor-constellation affordance increased as the industry concentrated after mergers. Large paint companies with more resources recognised research as important to improve quality, and they became more active in knowledge production, using tests and simulations of application conditions. At the end of the 1960s, cosmopolitanisation of paint technology was far less than in the case of reinforced concrete, which can largely be attributed to a lack of demanding customers and the fact that paint does not play a constructive role in higher-level configuration.

In the 1980s and 1990s a trans-local phase emerged when knowledge production became aimed at understanding the working of paint formulations (in addition to understanding structure-function relationships on the level of ingredients). I.e. research became aimed at developing a technical model of paint, and the notion of 'paint engineering' came into use. These efforts to produce translocal knowledge were induced by the emergence of the State and societal groups as demanding actors, and the increased concentration within the paint industry. Conventional paints were banned, and alternative paint systems needed to be developed and improved, which made existing empirical knowledge bases largely redundant. With the help of governmental research subsidies (aimed at creating alignments between university and industry), collective research was organised and for the first time academics became involved in the production of paint knowledge. The local-cosmopolitan division of labour became more substantial, and activities at the cosmopolitan level increased. If the cosmopolitan level starts to get a dynamic of its own, and a reversal occurs in which local practice become guided by outcomes of the cosmopolitan level, a cosmopolitan phase might emerge in the 21st century.

While both case studies have their complexities and contingencies, the contrast between the cases of reinforced concrete (rapid cosmopolitanisation) and paint (slow cosmopolitanisation) suggests that the emergence of demanding actors and a need to reduce risks and uncertainties beforehand are key affordances at the level of materials, especially in the transition from an inter-local to a trans-local phase. Without these affordances, cosmopolitanisation might well be slow and limited. In supplier-dependent innovation patterns, like in the case of paint, where there is no demanding customer, suppliers can take the lead. An example is the case of synthetic detergents, where suppliers like Shell and Esso took the lead in knowledge production when detergents were criticised for their detrimental effects on the environment. Paint technology remained an empirical technology with limited circulation for a relatively long time even though there were industry associations, research associations and professional societies. "Scientisation" of paint formulation did not occur until the 1980s, which indicates that it depends on affordance structures and is not self-evident.

In general, it can be argued that on the level of materials empirical knowledge, trial and error and testing will be important. Even in high-tech materials technologies (e.g. semiconductors, biotechnology) a large part of the relevant knowledge is empirical and relies on intimate knowledge of the material and its production. To make a configuration that works at this level does not necessarily require knowledge about how the performance can be explained. While at the level of artefacts interoperability between constituent components is largely a result of (intentional) design and is visible to the human eye, at the level of materials 'interoperability' between materials is the result of trials and tests — although theoretical insights can provide guidance in such efforts.

8.2.3 Cosmopolitanisation of magnetic video tape recording technology

The case study of magnetic video tape recording contrasts with the previous two cases: it is a case at the level of artefacts, and the technology emerged in a context which was prestructured by an electrical engineering community and an established industry with their infrastructures and collective reservoirs of knowledge about audio tape recording, television technology and electronics. The main knowledge producers were engineers who worked in industrial R&D labs and were members of professional societies — i.e. who had a cosmopolitan orientation from the start. Because of this starting point, there was no local phase. In the inter-local phase during the 1950s engineers in different companies shared the anticipation that video tape recording must be possible by building on the example of the audio tape recorder. Different variants were developed while companies kept an eye on each other's advances. Ampex won the "race" when broadcasters adopted their transversal-scan VTR in a prototype stage. It became the dominant design and Ampex created a virtual monopoly. With the end of the race, a trans-local phase (late-1950s—early-1960s) emerged in which knowledge was produced about how the performance could be made robust so as to ensure interchangeability of recordings. Knowledge about the VTR configuration became widely shared by engineers within the industry through presentations, demonstrations, publications, patents, cross-licensing agreements, joint ventures, and, in particular, reverse engineering. The VTR was standardised in a committee set up by a professional society in which manufacturers (Ampex and RCA) and customers collaborated. In the 1960s the *Quadruplex* VTR became a standardised and cosmopolitan technology, and knowledge on the *Quadruplex* product architecture became cosmopolitan as well. From a local "monstrosity" the *Quadruplex* had evolved into a cosmopolitan technology which was no longer dependent upon Ampex's expertise.

The affordance structure for cosmopolitanisation was relatively high. In addition to the affordances created by sedimented outcomes of previous processes and existing mosaics of regimes and infrastructures, the technology affordance was high. Interoperability required alignments with other manufacturers: with component suppliers as well as complementary manufacturers (licensees). It also required a thorough understanding of how the performance was achieved exactly, because the slightest deviations could result in incompatibility. As an assemblage, the VTR could be reverse engineered by engineers in rivalling companies with a common background. This made secrecy about the product design an unproductive strategy. The actor constellation consisted of a relatively small number of innovative companies which shared an engineering repertoire and the anticipation on a VTR. Typical for a R&D-dependent innovation pattern, manufacturers themselves were main knowledge producers and did not rely on collaborative modes to do research. For companies, patents were important as bargaining chips in cross-licensing negotiations and they gave reputational rewards as well. Broadcasters were demanding customers who participated in production of knowledge on the *Quadruplex* and helped to make the "monster" robust.

In the 1960s, a new inter-local phase with race dynamics emerged as firms anticipated that a consumer VTR should be possible as well. While building on a shared repertoire, engineers in industrial labs developed different solutions for an anticipated market. Advances by one company were emulated by competitors. The stakes were high, so firms tried to anticipate on first mover advantages. Sufficient mass was required to win over consumers. Companies sought alliances to increase chances of success. In such alliances agonistic knowledge sharing occurred, and in the early 1970s, different VCRs had very similar product configurations. Eventually, in a trans-local phase, JVC's VHS format won a 'battle' of standards, and became the dominant design, and with it knowledge on the VHS (which was largely shared by then) became dominant as well. The VCR took twenty years to become commercialised, and during this period the affordance structure co-evolved with cosmopolitanisation processes. Interoperability requirements and anticipated network externalities created affordances for making alignments with other manufacturers and suppliers. Knowledge on the basic product configuration became quickly shared within the engineering community, and manufacturing knowledge (which could be kept secret) became important as a competitive asset. Anticipations on network externalities in the consumer market created affordances for alliances in which knowledge was shared.

While interoperability played a specific role in the case of video recording, it can be argued that in general technologies at the level of artefacts create higher affordances for the production of translocal knowledge than technologies at the level of materials. Rivals can assess each others' technologies more easily, which increases interdependencies. Anticipations on dominant designs create affordances for alignments and agonistic knowledge sharing. Such sharing, which also happens before a dominant design has emerged, adds to a collective repertoire which crystallises and gets institutionalised after a dominant design has emerged.

8.2.4. Cosmopolitanisation of air traffic control systems

The air traffic control case was an extreme case. ATC systems are highly complex systems in which multiple subsystems have to interoperate to create an overall performance, i.e. safe and efficient air traffic. Cosmopolitanisation was again a phased process, with a local, inter-local, trans-local and an emerging cosmopolitan phase. In the early years, ATC systems were loosely coupled, ad hoc configurations with humanware as highly flexible (interfacing) elements. As the system grew more complex and interconnected in successive generations, affordances for systematic and proactive knowledge production at the level of the systems architecture increased. Initially, this architectural knowledge was system-specific (in the inter-local phase; 1940s—1980s). When international interoperability became recognised as important because an increase in international air traffic threatened to overload the international patchwork of ATC systems, concepts were developed which transcended national specificities (trans-local phase; 1980s—2000s). ICOA's CNS/ATM concept, developed independently of any specific national ATC system, became a guiding principle for the design and implementation of ATC systems which were designed as interoperable elements in a global architecture (cosmopolitan phase; 2000s—). Cosmopolitanisation involved the development of an increasingly complex division of labour with a central role of achitectural actors, and international infrastructures for knowledge exchange and collaboration in R&D. In the United States, the FAA contracted systems engineering organisations to ensure an architectural approach to 'modernisation' of the U.S. ATC system. In Europe, Eurocontrol became an important actor in the production of knowledge required for harmonisation and integration of national ATC systems. Internationally, FAA and Eurocontrol increasingly coordinated their activities and collaborated in R&D.

The technology affordance structure was characterised by high complexity which created dual affordances. One the one hand it induced efforts to reduce complexities and uncertainties beforehand. On the other hand, the complexity and uniqueness made it difficult to create knowledge which was not tied to a specific systems configuration. This inherent threshold was overcome when national systems became designed and implemented as parts of a global ATC architecture, guided by global concepts. The systemicness of the technology also meant that backward and forward compatibility were important. This created path dependencies. Anticipations on such requirements induced a planned and coordinated approach to architectural design and implementation rather than a battle of standards or a race towards a dominant design. Typical for large complex systems, the ATC market was bureaucratically administered and contestability was low (Hobday, 1998). There were various users and many regulations which had to be taken into account in the design and implementation. Thus, socio-political and socio-cognitive processes were interwoven in cosmopolitanisation of ATC systems.

The actor constellation was characterised by a mission-oriented innovation pattern and a monopsonistic industry structure. There was a dominant and demanding mission-actor which only certified technologies that could demonstrate reliability and interoperability. The actor constellation co-evolved with cosmopolitanisation processes: systems engineering organisations came to play an integrating role at the architectural level, and the ATM industry concentrated and became international, thus increasing affordances. Large ATM companies became experts in recontextualisation of cosmopolitan systems architectures.

8.2.5 Cosmopolitanisation patterns across the four case studies

If the four case studies are collated, what patterns can be identified? In the first instance, I will identify patterns in how knowledge becomes translocal for different levels in the technical hierarchy. A key process or mechanism is the sharing of knowledge, which is always accompanied by transformations of knowledge.

In the case of reinforced concrete, the production of translocal knowledge revolved around understanding and modelling the performance of the composite material so as to make it reliable and calculable — which required standardisation of raw materials and disciplining of construction practices. In the case of paint, the eventual production of translocal knowledge also revolved about understanding and modelling the performance of paint formulations, which required uniformity of paint ingredients and the disciplining of formulation practices (which was less difficult because paints were made in factories rather than on location). In the case of video recording, knowledge production was not so much about understanding and modelling the performance, but rather on how an anticipated performance could be achieved, and how a promising "monstrosity" could be made robust and interoperable. Magnetic audio tape recording provided a model on which video recording could be based. In other words, the production of knowledge revolved not so much around understanding the working of the video recorder, but on how to combine and assemble components into a robust product configuration which could achieve an anticipated performance. Knowledge production occurred on two levels: on the level of the components (e.g. tapes, heads) and on the level of the artefact. In the case of ATC, production of translocal knowledge revolved around creating guiding concepts for the integration and harmonisation of ATC architectures into a global (and seamless) system of systems. Cosmopolitanisation of ATC is then a socio-cognitive as well as a socio-political achievement because many different actors and locations need to be aligned to create a performance.

By definition, translocality depends on circulation and (agonistic) sharing of knowledge. Sharing at the level of materials required the development and articulation of technological knowledge which could make the performance predictable and understandable. In the two case studies this "know-why" knowledge was achieved through collaborative research. Sharing on the level of artefacts meant that different actors emulated each others' advances and created alliances in anticipation of markets, and that a dominant design emerged which became part of a dominant knowledge repertoire. Sharing at the level of systems meant that architectures were developed in which each system was an interoperable element in an overall system, and that a global architecture was developed in which each national architecture was an interoperable element in a world-wide system. It is clear that the influence of socio-political and socio-economic dynamics is larger in higher levels of the technological hierarchy.

In addition, the innovation patterns in the four case studies were different, and this also affected cosmopolitanisation. In the case of reinforced concrete, an innovation pattern emerged with characteristics of a user-driven innovation pattern with dominant and demanding users. The case of paint was a clear example of a supplier-dependent innovation pattern. In the case of video recording there was a R&D-dependent innovation pattern, while ATC was an example of a mission-oriented innovation pattern. These innovation patterns shaped cosmopolitanisation in different ways. An important difference can be found in the local-cosmopolitan divisions of labour which emerged. In the case of reinforced concrete, demanding customers were part of such a division of labour. In the case of paint, suppliers were main knowledge producers. In the case of video recording, manufacturers themselves played a prominent role. Finally, in the case of ATC, mission actors and their systems engineering consultants played an important part. Thus, the production of translocal knowledge was afforded by different actor constellations and was carried by different local-cosmopolitan divisions of labour. Innovation patterns resulted in differences in pace of cosmopolitanisation, the way thresholds were overcome, and how local-cosmopolitan divisions of labour unfolded.

Notwithstanding differences in how collective knowledge reservoirs were created and maintained, how infrastructures emerged and how local-cosmopolitan divisions of labour unfolded, there is a general pattern of four phases separated by transitions which was identified in all four cases. The four phases worked out differently in terms of. In Table 8.1, the patterns identified in the four case studies are summarised.

Table 8.1 Cosmopolitanisation patterns in the four case studies

	reinforced concrete	*paint*	*VTR*	*VCR*	*ATC*
local phase	1850s–1870s: local solutions, trial and error / high variability, trade secrets "Success without understanding"	until 1910s: experience-based; formulation knowledge local and tacit; variability of materials; little understanding of process, but not needed to satisfy demand	*no local phase* video (tape) recording was anticipated, given success of audiotape recording, demand from TV. World of electrical and electronic engineering was cosmopolitan already	*no local phase* VCR branches off from VTR developments to address other sectoral users and mass-consumers market	1920s–1940s: local control units at airports, with limited communication support, and some routing requirements and en-route centres
transition	local solutions developed into building technology; new type of customers	large industrial customers; standard test methods required	anticipated design ("promise") to be filled in technically	a new race dynamic, driven by anticipated design to be filled in technically	internationalisation of air traffic and anticipation on international standards
interlocal phase	1870s–1890s: proprietary systems protected by patents (= regional sharing) "Understanding within systems"	1910s–1970s: dual market, with industrial requirement of uniform and high-performance paint met by upgraded natural materials and synthetic materials; UK and Dutch industry research associations (also study of formulations); After WW II chemical industry supplied new materials, sharing through supplier-domination (later integration)	1940s–early 1950s: "monsters" were produced and improved through feedback from lead users; secrecy until patent position was secured; prototypes demonstrated to signal (also to rivals) and create alignments with actors in the chain	late 1950s–early 1970s: miniaturisation, and variety of basic designs (including helical scan) and variety of prototypes within each basic design. Shared engineering knowledge reservoirs, but separate design trajectories. Imitation. No real customers yet.	1940s–1980s: standardisation at level of subsystems rather than overall architecture. New technology added to improve performance; automation at national level; responses to failures and risks, which included reflection on overall architecture.
transition	risk reduction by anticipatory calculation, required by demanding customers / agencies	challenge of health, safety and environmental issues	1956: Ampex convinced major broadcasters to help develop their prototype	shake-out, and remaining protagonists created alliances (networks)	projections of substantial increase in air traffic, emergence of transnational organisation
translocal phase	late 1890s–1910s: standardisation (building codes and other rules) underpinned by theory and data; included research and standardisation of raw materials and disciplining of process; journal articles and handbooks	1980s–present: collaborative research (+ government support) to develop technical model of paint; 'paint engineering' as label	late-1950s–early-1960s: cross-licensing with RCA; reverse engineering in Japan; standardisation by defining best practice in working party of professionals; Quadruplex as dominant design Agonistic knowledge sharing, plus "inventing around" established patent positions leading to a reservoir of technological options to achieve the performance (not taken up because of lock-in, cf. exclusion of Toshiba's helical-scan alternative, demonstrated in 1960)	early 1970s–1980s: collaborations in anticipation of eventual standard. Agonistic sharing of knowledge is part of the battle of standards.	1980s–2000s: concept of a global ATC architecture (guiding principle); research on further national improvements was coordinated; only a few large companies remain active in design, implementation and integration of ATC system. Context-knowledge remains important to implement a system on location

transition	interdependencies in reinforced-concrete industry and new structures	no reversal has occurred yet where cosmopolitan level takes the lead	gradual change to world-wide and exclusive design (also because of backward compatibility)	during 1980s, VHS won out (de facto standard)	new CNS/ATM concepts (e.g. 'free flight')
cosmopolitan phase	1920s–1940s: two-level dynamic, normal practices defined at the cosmopolitan level; collaborative research; courses and training secular change: aftermath of WW II 1950s–present: applied research, industrial associations, other intermediary actors; link with building challenges, and taken up at the cosmopolitan level		1960s–1970s and beyond: standardised and cosmopolitan technology, with incremental improvements. After 1970s, alternatives emerged.	late 1980s: VHS as dominant design made knowledge about VHS product architecture dominant as well.	2000s and beyond: ATC architecture design and implementation as part of a virtually seamless "global" CNS/ATM architecture based on satellite technology and worldwide information and communication infrastructures

The local phase in the case studies was characterised by: various local solutions developed by innovative producers who created their own proprietary expertise based on accumulated experiences and trial and error (reinforced concrete); various local solutions developed by paint formulators who created their own proprietary expertise based on accumulated experiences and trial and error, supplemented with knowledge from travelling experts and handbooks (paint); and a loosely coupled configuration of local units and technologies which had emerged in an ad hoc way (ATC). In general, the local phase can be characterised by a heterogeneous set of local practices that are relatively independent and create their own knowledge which is not shared with others.

The transition from local to inter-local in the case studies was induced by: novelty growing out of niches and introduction in larger markets with professional customers (reinforced concrete); the emergence of large industrial customers who required uniform, repeatable performances (paint); a shared expectation that a demand from professional customers could be filled in (broadcast VTR); a shared expectation that an existing technology could be improved for a mass market (consumer VCR); and an anticipation on international interoperability standardisation (ATC). In general, it can be argued that competition between producers to attract customers (whether present or anticipated) will play an important role in this first transition.

The inter-local phase in the case studies was characterised by: sharing of knowledge within networks of licenser/licensees and competition between different technological variants developed and promoted by (groups of) contractors in the context of a collective attempt to win over professional customers (reinforced concrete); sharing of findings of collective research on common problems/challenges between members of (research) associations and sharing between dominant suppliers and paint formulators (paint); limited disclosure of knowledge to create alignments and show progress (broadcast VTR); limited disclosure of knowledge to create alignments in anticipation of mass-market (consumer VCR); and first efforts to create architectural knowledge to integrate subsystems into a national systems architecture in the context of international standardisation (ATC). In general, it can be argued that the inter-local phase is characterised by sharing within networks, alliances, joint ventures, supplier-producer relations, associations or within an (emergent) architecture.

The transition from inter-local to trans-local in the case studies was induced by: a need to reduce risk by anticipatory calculation at the instigation of demanding customers and agencies (reinforced concrete); the challenge of health, safety and environmental issues raised by governments and societal groups (paint); the requirement of professional customers to achieve interoperable and reliable product (broadcast VTR); the need to create sufficient mass (consumer VCR); and anticipation on the need to integrate and harmonise systems into one architecture (ATC). In general, it can be argued that for this transition "high demands" with regard to the performance (in terms of reliability, safety, interoperability) will play an important role.

The translocal phase in the case studies was characterised by: increased production and circulation of translocal knowledge (e.g. handbooks, articles) and standardisation (in committee of professional society) underpinned by theoretical knowledge and experimental data up to a technical model, as well as standardisation of raw materials and application (reinforced concrete); development of technical model of paint based on collaborative research and involvement of academics as well as concentration within industry (paint); sharing of knowledge between manufacturers and professional customers resulting in standardisation of dominant design and definition of best practices in a working party of a professional society, sharing between licensers and licensees, sharing within alliances and joint ventures, as well as reverse engineering by rivals (broadcast VTR); knowledge sharing in alliances, reverse engineering, and agonistic knowledge sharing in the context of a battle of standards (consumer VCR); and collaborative development of a global architecture as a guiding principle and coordination of research in anticipation of global harmonisation and integration, as well as concentration within industry with a few remaining global players (ATC). In general, it can be argued that the translocal phase is characterised by increased production and circulation of translocal knowledge, standardisation efforts based on consolidated knowledge, and beginning stabilisation of divisions of labour.

The transition from trans-local to cosmopolitan in the case studies was induced by: institutionalisation of translocal knowledge in building codes, standards, handbooks and textbooks (reinforced concrete); establishment of a *de facto* industry standard and subsequent official standardisation and lock-in of customers (broadcast VTR and consumer VCR); and international agreement on, and uptake of, CNS/ATM concepts as guiding principles (ATC). In general, it can be argued that institutionalisation and standardisation are required to achieve a reversal.

The cosmopolitan phase in the case studies was characterised by: emergence of 'normal practices' defined at the cosmopolitan level, continued collaborative research, courses and training (reinforced concrete); incremental improvements of dominant design and uptake of knowledge in collective knowledge reservoirs (VTR and VCR); and design and implementation of ATC systems as part of virtually seamless "global" architecture (ATC). In general, it can be argued that the cosmopolitan phase is characterised by cognitive structuration of local practices by knowledge produced at the cosmopolitan level, i.e. the emergence of a cosmopolitan technological regime which enables and constrains local practices.

The overall patterns in cosmopolitanisation which I have drawn out of the analysis of the case studies can be summarised as in Table 8.2. The key finding, independent of the details of the phases and transitions, thus is that cosmopolitanisation is not a linear process, but happens in phases with transitions from one phase to another. A crucial transition is from inter-local to trans-local when knowledge production becomes disembedded from specific local contexts. In the case studies, this transition relates to (actual or projected) increasing demands on performance and the anticipation on such demands through modelling, comparing best practices and the identification of overall design guidelines or guiding principles. In general, increasing demands on performance is the key point. How this comes about, and what subsequent steps are, depends on the array of affordances.

Table 8.2 Four phases in cosmopolitanisation

	General characteristics
local phase	Heterogeneous set of relatively independent local actors who create their own knowledge which is sufficient for their purposes. No collective knowledge reservoir, no infrastructure, no local-cosmopolitan division of labour.
transition	Increasing interactions and interdependencies between local actors, in terms of shared expectations about the technology and some competition.
inter-local phase	Increased circulation of knowledge within networks, alliances, joint ventures, supplier-producer relations, associations, or within emerging architectures in case of large complex systems.
transition	Increased demands upon performance (in terms of reliability, safety, quality, interoperability).
trans-local phase	Increased production and circulation of knowledge intended to be translocal, standardisation based on consolidated knowledge, and beginning stabilisation of local-cosmopolitan divisions of labour. There are actors at a cosmopolitan level but their actions are ad hoc.
transition	Institutionalisation and standardisation creating dominant rules.
cosmopolitan phase	Socio-cognitive structuration of local practices by knowledge produced at the cosmopolitan level, i.e. an established technological regime. Shared collective knowledge reservoir, supported by infrastructure and local-cosmopolitan division of labour. Actors at cosmopolitan level play a structural role.

8.2.6 Affordances for cosmopolitanisation

To find out what can be learned from the case studies about the role of various affordances, and understand their effects, I shall discuss them separately. This is a reduction of complexity, because they occur together, and it is the array of affordances which explains the steps toward cosmopolitanisation. But such a reduction is necessary to understand what might happen in other cases, with a different set-up. To keep at least some of the complexity, I will refer to some of the details of the cases, even if that makes my text somewhat repetitive compared with earlier sections.

Technological affordances

In my conceptualisation (Chapter 2), the technological affordance structure consisted of "complexity", "repeated performance", "risk", and "megamachine". My hypothesis was that the level of complexity shapes the conditions for knowledge production: the more complex, the more substantial the requirements for coordination and exchange between actors and locations to create a configuration that works. Such requirements will create an affordance for the production of translocal knowledge. In the two case studies with a low level of complexity (reinforced concrete and paint) knowledge production indeed remained tied to separate local practices, until other affordances induced interlocal and translocal knowledge production. In the case study with a medium level of complexity (video recording), manufacturers created alignments with complementary producers, suppliers and professional customers to achieve a reliable and interoperable performance. These alignments created affordances for the production of translocal knowledge. In the case study with a high level of complexity (ATC) the creation of alignments between multiple actors and locations was crucial to create an overall performance. At the same time, however, and again because of the complexity it was very difficult to create translocal knowledge at the level of the overall system. When alignments between national systems became important, production and circulation of knowledge on the architectural level increased. Thus, the hypothesis about complexity as requiring alignment and thus creating affordances for production and circulation of translocal knowledge is supported by my findings. What I can add now is that a high level of complexity creates a dual affordance because the requirement of making alignments is counterbalanced by the uniqueness and singularity of the complex configuration.

With regard to the second affordance, my hypothesis was that situations in which repeated performance is required create affordances for the production of translocal knowledge. In the two cases at the level of materials, manufacturers were challenged to achieve performances time and time again with variable materials and variable application conditions. They created empirical rules based on accumulated experiences. Eventual translocality depended upon standardisation of materials, production processes, and application conditions. In the case at the level of artefacts, video recording, the challenge of repeated performance also played a role because video recorders of different series had to be interoperable. I.e., standardisation of performances was crucial, and this created an affordance for production of translocal knowledge. Note that this affordance links up with the complexity affordance, because a standardised performance required alignments with suppliers and complementary producers. In the case of ATC, there was no question of repeated performance since each nation developed its own unique complex configuration which had a very long life-span.

Thus, the hypothesis about the affordance created by a challenge of repeated performance is supported by findings from my case studies. Whether translocality will be achieved, depends on other affordances as well, since producers will not necessarily be induced to disclose and share their expertise.

The third technological affordance was the level of risk and uncertainty. My hypothesis was that situations which are characterised by a high level of risk and uncertainty create affordances for the production of translocal knowledge as this is seen to reduce risk and uncertainty to a manageable level. In the case of paint, the low level of risk created few affordances to invest in knowledge production. Failure of a coating was usually repairable by applying a new coating, although this could have repercussions in terms of liability and reputation. In the case of reinforced concrete, the level of risk was much higher. Failure of reinforced concrete in constructions could result in collapsing structures and this created affordances to try to understand and predict the performance before construction. Learning from failure happened, but was a costly strategy. This affordance worked especially on professional customers who needed to be able to take responsibility for the performance. In the case of video recording, while reliability was a major user requirement, the level of risk was limited because eventual failures could be mended with repair work. In the lab much could be learned from failures of prototypes before VTRs were mass-produced and shipped to customers. In the case of ATC, risk created a high level of affordances, because failure could have catastrophic consequences. Before ATC technologies are implemented they have to be tested and certified, and in simulations it is tried to predict the effect of new technologies in the overall system. It can be concluded that a high level of risk indeed creates affordances to produce robust and translocal knowledge, even if this is conditional on the occurrence of strategies to reduce risk and uncertainty.

A final hypothesis was that there is a fourth type of affordance deriving from the requirements of a system level on the components and devices which are its parts. Coordination is easier when components and devices are standardised in terms of performance and interconnection. Such effects on components are visible in the way resistors, capacitors and other electrical components are now completely standardised which allows the designer to concentrate on how they are put together in the system. This last kind of knowledge is then easier to transfer, in a sense because it is more abstract. Such a situation obtained in the case of ATC when safety and efficiency required an integration of subsystems into one architecture, and systems engineering knowledge was produced. In this case, the idea of a megamachine is clearly applicable, because not only the technical parts, but also skills and behaviour of controllers and pilots had to be standardised (to some extent). At lower levels in the technical hierarchy, the combination of system and components is less evident. For materials, the nearest equivalent of the effect of this affordance would be the production of knowledge about assemblage in general, or formulation in general (say, the abstract version of paint engineering). For artefacts like videorecorders, one could see a double dynamic: abstract knowledge about assembling (not visible in the case study though) and an effect on the development of video tape recorders of their being part of the megamachine of TV broadcasting. Clearly, there are affordances here, but of different kinds, and not always linked to the production of translocal knowledge. One lesson from the case studies is therefore that the affordance as originally formulated must be rethought.[1]

Another lesson is that when the technology has itself characteristics of a megamachine, a special kind of knowledge about architecture and disciplining can emerge and circulate when it is transformed in a more abstract form than concrete skills of assembling and managing.

Table 8.3 Technology affordances

	Affordances related to:			
	Complexity	Repeated performance	Risk	Megamachine
Reinforced concrete	—	+	—/++*	—
Paint	—	+	—	—
Broadcast VTR	+	+	+	+
Consumer VCR	+	+	+	+
ATC	++	—	++	++

—: no affordance
+ : affordance
++: major affordance
* risk depends on the type of application of reinforced concrete

The findings in the case studies further suggest that technological affordances are mixed and may change over time, and that technological affordances can work in different (sometimes opposite) directions. In situations in which complex technologies are produced, knowledge production will be afforded by dual affordances: translocality is rewarding in terms of creation of alignments, improvement of manageability and reduction of risk, but also costly and difficult to achieve given the complexity and local uniqueness. Situations in which relatively simple technologies are produced, create little affordances in terms of creation of alignments, improvement of manageability and reduction of risk, but on the other hand do create affordances for repeated performance and standardisation.

The affordance structure is underdetermined by technology affordances alone. Or putting it in common-sense terms: one cannot understand the evolution of technological knowledge by seeing it only as a response to the complexity, risk, and repeated performance of the technology. The overall affordance

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[1] A starting point for such rethinking can be found in the way Constant (2002: 1247) discusses and expands Vincenti's claim "that the "higher" in the system hierarchy a design issue is defined, the greater the design freedom or the less the degree of purely technical constraint. Conversely, the lower in the level in the system hierarchy, the more likely that design is constrained by technical criteria prescribed at a higher level. But Vincenti also emphasizes that design "takes place iteratively and interactively (both vertically and horizontally) throughout the hierarchy.""

structure depends on how technology affordances link up with actor-constellation affordances and secular changes. In other words, how complexity is made manageable, how repeated performance is achieved, how risk is reduced, and how megamachine dynamics work out, depends on how the actor constellation evolves and how secular changes are taken up. In addition, technology affordances and actor-constellation affordances are not independent. For instance, to produce large complex systems mission-oriented innovation patterns are required, and such patterns, once in place, enable the production of large complex systems. High-tech complex artefacts (as well as high-tech materials) occur in R&D dependent innovation patterns, and materials (and less complex artefacts) in supplier-dependent or user-driven innovation patterns.

Actor-constellation affordances

In Chapter 2, actor constellations were introduced as affordance structures to understand how collective goods can be produced. One feature of industry structure, many small or a few large manufacturers, is clearly important because the chance that a collective good is produced decreases with the number of relevant actors. Similarly, the existence of a dominant actor increases the chance that a collective good will be produced through his action, pressure, or mobilisation of allies. For my question about cosmopolitanisation of technological knowledge, the relevant dominance of actors is linked to the kind of innovation pattern (Pavitt, 1984; Van de Poel, 1998) that obtains. The interdependencies and role relations between suppliers, producers and customers with respect to innovation and related knowledge production are often stabilised, and thus enable and constrain the actions of the various actors.

Another route to the production of a collective good is the action of intermediary actors or third-parties who have a stake in the production of such a good, and will therefore work toward overcoming the threshold. An example, discussed in Chapter 2, were associations of professional engineers who could profit from a shared knowledge reservoir and work towards its improvement. Some of these intermediary actors, like industry associations, are collective actors whose existence is not automatic: they have to be "produced" themselves.

This skeleton argument about the affordance for cosmopolitanisation of technological knowledge can now be fleshed out with the help of the case studies.

A user-driven innovation pattern was visible in the case of reinforced concrete. Typical for a user-driven pattern is that there are professional customers who are "performance-sensitive because the carrying out of their professional activities depends on the technology they use" (Van de Poel, 1998: 62) and that they are often actively involved in knowledge production themselves. The affordance for the production of translocal knowledge lies in the combination of there being a dominant actor, the professional customer, and his performance-sensitivity. In the case of reinforced concrete, such professional customers emerged toward the end of the nineteenth century when the new technology had shown its promise. They wanted to be convinced of the reliability of the technology, and actively participated in the production of the knowledge which was required. The eventual collective theoretical-experimental project in which translocal knowledge was produced can be largely understood as a result of affordances created by the dominance and performance-sensitivity of professional customers. Their role overcame the limitations of an industry with (at that time) many small manufacturers. Just as important for the kind of knowledge production was the fact that they were demanding in terms of reliability and calculability.

A supplier-dependent innovation pattern was visible in the case of paint. Typical for such patterns are large "science-based" suppliers and manufacturers who are not very active in knowledge production themselves and rely on assistance from suppliers and accumulated experiences. The latter was visible in the paint sector from the beginning, the former only after the introduction of synthetic chemicals. While a supplier-dependent innovation pattern creates affordances for suppliers (e.g. to maintain their competitive position vis-à-vis other science-based suppliers), manufacturers can limit themselves to follow what others do. In the case of paint, formulators were indeed not very active in technological knowledge production about formulation and the role of various ingredients, but relied on knowledge from dominant suppliers who helped them with development of formulation methods for new ingredients. Knowledge sharing between paint manufacturers was limited, and relations with suppliers were more important. However, for a long time suppliers were not really interested in paint because it was a small and fragmented market. (In other supplier-dependent innovation patterns suppliers might be more active in knowledge production on the level of the formulation/artefact. An example might be synthetic detergents, where the big suppliers Shell and Conoco rather than the detergent manufacturers themselves responded, in the late 1950s, to the challenge of surface water pollution by establishing a large and successful R&D effort to create biodegradable ingredients – this in contrast with the later challenge of phosphates in detergents where there were no suppliers working towards an alternative (De Man, 1987). Interestingly, cosmopolitanisation of paint knowledge increased when governments banned conventional paint systems, and manufacturers could not fall back on their empirical knowledge bases — a demanding actor had arrived on the scene.

An R&D-dependent innovation pattern was visible in the case of video recording. Typical for such patterns is that manufacturers are "science-based" firms with in-house R&D. Knowledge production and access to collective knowledge reservoirs are vitally important to remain competitive. "Typical for an R&D-dependent innovation pattern is that promises initially apply to new technical configurations that are not yet realized." (Van de Poel, 1998: 64). I argued that such patterns create affordances for cosmopolitanisation. In the case of video recording, promises and anticipations were shared from the outset, a framing in which manufacturers became part of a strategic game, a race for the winning videorecorder. Once the race was won, knowledge became part of a collective reservoir. It was presented in forums (also for reputational rewards), it was shared within alliances/joint ventures/cross-licensing deals, and it was reverse engineered by rivals. Thus, while there was no dominant actor, the competition within a shared framework of expectations, drawing on a shared reservoir of knowledge, allowed strategic sharing of knowledge and later, sharing and improving of knowledge relevant to the dominant design. R&D-dependent innovation patterns need not always lead to such dynamics, but when there is a generally recognised technological promise, it will certainly happen. The case of fuel cells, over the last few decades, is an interesting case in point, also because there is still no closure (Schaeffer 1998, Avadikyan *et al.*, forthcoming 2003).

A mission-oriented innovation pattern was visible in the case of ATC. Typical for such patterns is that governmental actors define the functions to be fulfilled by a technology. In military technology, this is very clear. Mission actors can then act, in Disco's phrase, as cosmopolitan tutors to localist contractors, and for example, require contractors to exchange knowledge. In general, this pattern has a recognised dominant actor (even if he has to negotiate with contractors, as well as other government actors and democratic representatives). Cosmopolitanisation is further afforded because mission actors need a knowledge base to supervise contractors, and because producers need to show their knowledge production to build reputation and remain competitive. A further feature is visible in the case of ATC because knowledge production was configuration-specific until the 1980s. The complexity affordance with its reference to local, unique situations dominated the earlier knowledge production. When aviation authorities from different countries began to coordinate their plans and initiated collaborations, cosmopolitanisation increased. The case study suggests that although the dominance of mission-actors is expected to create an affordance for the production of collective goods, this can be counteracted by a technology affordance of complexity/uniqueness. Mission-oriented patterns might well be linked to complex technological systems like nuclear power plants or large water works (Van de Poel 1998), and thus always show this duality. There might be a second-order translocal knowledge, visible in the general skills of engineers to adapt the general design to local circumstances.

As I showed when discussing phases and transitions in cosmopolitanisation of knowledge, the role of demanding actors must be traced, because it is their demands which set in motion the development of new and more cosmopolitan knowledge. A further, and important aspect of actor-constellation affordances is thus the appearance of demanding actors. When this will happen, and who these actors are, can be historically contingent. The large furniture firm Ikea turned out to be a demanding actor for the paper industry, when it required environmentally-friendly production of paper for its catalogues – which are the second largest publication in the world, after the Christian Bible, so it had enough power to be demanding (Håkansson, industrial network analysis). The possibility to be a demanding actor for knowledge production is related to the nature of the innovation pattern. In the case of a user-driven innovation patterns (exemplified by reinforced concrete), performance-sensitive customers can be demanding and thus create affordances for cosmopolitanisation. In the case of supplier-dependent innovation patterns (exemplified by paint), demanding actors might well be absent, although in the case of paint governmental actors came to act as demanding actors and triggered a transition from an interlocal to a trans-local phase. In the case of R&D-dependent innovation patterns (exemplified by video recording) manufacturers themselves are likely to act demanding actors (for themselves as well as for their suppliers and partners). In the case of mission-oriented innovation patterns (exemplified by ATC) the mission actor is demanding.

The role of third parties, that is, parties not in the business chain, who may come to act as demanding actors should not be forgotten. For instance, insurance companies may impose requirements and may themselves become active in the production of such rules based on accumulated experiences and findings. Classification societies in shipbuilding (Andersen and Collett, 1989) are a clear example of an insurance company which evolved into an engineering consultant which became active at the cosmopolitan level. In the present case studies, such third-party dynamics were not emphatically present, but traces could be found as when insurance companies get concerned about collapsing buildings.

Because of thresholds to move towards the production of collective goods, in my case, translocal knowledge, cosmopolitanisation may not take off until intermediary actors have emerged who take a responsibility for producing and maintaining translocal knowledge. Once such intermediary actors become an accepted part of the actor-constellation, cosmopolitanisation can gain further momentum. The existence of such intermediary actors is historically contingent (even if there are some general patterns, see below, on secular changes), and in a sense, itself a case of production of a collective good. This is clearly the case for branch organisations and industry associations, which are 'collective actors' as discussed already by Olson Jr. (1965).

Professional engineering societies, with their sections and working groups and committees, played the role of intermediary actors in all cases, and were particularly important for reinforced concrete and video recording, and less emphatically for paint (where branch organisations and industrial research associations played this role). Because of the engineers' interest in performance, there will be a *de facto* alliance with (often large) performance-sensitive professional customers as these figure in user-driven innovations patterns. In the case of reinforced concrete, it was clear how engineering societies provide forums, and thus an infrastructure for circulation and exchange, and sometimes also for standardisation. As Disco (1990) has emphasised, such an enabling function goes hand in hand with selective exclusions and attempts to become and remain credible. In this case one also sees a sequence which may well occur in other cases: After professional customers had accepted the new technology, the reinforced-concrete industry grew, and other intermediary actors such as industry associations and research associations were established and became important.

After the Second World War, the governments set up sectoral research centres. I expect such a sequence to occur when most manufacturers are small and do not have R&D capabilities. The creation of various 'collective actors' is then a condition for the production of translocal knowledge as a public good.

In other cases, for example in supplier-dependent innovation patterns where the manufacturers are content to build on experience, good market relationships, and the knowledge embodied in what is supplied to them, the sequence may be different. In the case of paint, the industry formed an industry association when they were confronted with new ingredients, new customers, and international competition. In the UK, the government subsidised a research association which came to play an important part in cosmopolitanisation. Once present, these intermediaries took initiatives to organise for collective research to solve common problems, if only to justify their existence. As other industries professionalised, the paint industry also tried to establish professional societies, to remain competitive with other industries in the labour market. In the transition towards the translocal phase (cf. Table 8.1), stimulated by government regulation and other pressures on conventional paint systems, industry associations and professional societies were stakeholders at the collective level and played a coordinating role in the organisation of collaborative research and dissemination of its results. By that time (1980s), such an approach was generally accepted. But its success does depend on the presence and activities of the right intermediary actors.

In the case of videorecording, the role of professional societies and industry associations (already present in the electrical and electronic engineering world) was mainly supportive in that they offered forums for exchange, circulation, standardisation and establishment of best practices. I.e., they provided an infrastructure for cosmopolitanisation, rather than that they enabled collaborative research as such. This will be related to the fact that R&D is organised within companies, and to the dynamics of an R&D-dependent innovation pattern. The R&D laboratories play a role in the sharing of knowledge, within the limits set by the strategies of the firm and appropriability considerations. Such interactions have been analysed in the literature (cf. Chapter 2; for a brief overview see also Franke and Shah, 2003: 158-160), and my case study is a further example.

The case of air traffic control shows another sequence, which may be common in mission-oriented innovation patterns: there is often a monopsonistic industry structure in which the mission-actor is responsible for the performance, and orchestrates the knowledge production and sharing. The industry works for a common "cosmopolitan" principal, and it is his action and his role which induces certain knowledge sharing and creation of translocal knowledge. In the case of ATC, the FAA was supported by a range of intermediary organisations to assist in the production of architectural knowledge. On an international level there was an infrastructure of transnational organisation for standardisation and coordination of national systems. Eventually, the transnational organisations provided forums for coordination and the development of global guiding concepts. Many of the stakeholders organised themselves in associations and societies to influence decision-making at the architectural level.

In other examples of a mission-oriented innovation pattern, for instance safe nuclear reactors and flood barriers as described by Van de Poel (1998), one sees similar orchestration by the mission actor, stimulated by various stakeholders including engineers and their societies. The net effect is an increase in knowledge, with the actors, how to contribute to such a system in other places.

Thus, intermediary actors are likely to play different roles in different innovation patterns. While their roles may vary, their presence is required for a collective knowledge reservoir to be produced and maintained. In all patterns, they provide an infrastructure for circulation and exchange, and they help overcome thresholds, especially in cases when there are many small producers.

Table 8.4 Actor-constellation affordances

	Affordances related to:			
	Innovation pattern / dominant actor (in brackets: specification)	Demanding type of actor (in brackets: specification)	(Original) industry structure (in brackets: specification)	Existence and role of intermediary actors
Reinforced concrete	+ (user-driven: customer)	+ (professional customers / inspectorates)	— (many small manufacturers)	+
Paint	— (supplier-dependent: supplier)	+ (government / societal actors))	— (many small manufacturers)	+
Broadcast VTR	+ (R&D-dependent: manufacturer)	+ (professional customers)	+ (oligopolistic)	+
Consumer VCR	+ (R&D dependent: manufacturer)	+ (anticipated consumers)	+ (oligopolistic)	—
ATC	+ (mission-oriented: mission actor)	+ (mission actor)	+ (monopsonistic)	+

—: no affordance
+ : affordance

Secular changes

The general point, as made in Chapters 1 (section 1.3) and 2 (section 2.3.3), that cosmopolitanisation never starts from scratch but is prestructured by the historical setting, and sedimented outcomes of earlier cosmopolitanisation processes, is clearly visible in the case studies. Secular changes affect cosmopolitanisation directly, as well as indirectly through actor-constellation affordances (e.g. when professional societies become part of the actor constellation) and technology affordances (e.g. the rise of large technical systems during the twentieth century). In any particular case study, one cannot do much more than identify such secular changes and their effects, whatever these are. It would be another study to draw on the literature and trace such changes themselves and try to understand them. In Chapter 1 (section 1.3) I gave a brief sketch, and elements of it return in the case studies. In section 2.3.3, secular change was taken up as a third kind of affordance, enabling and constraining cosmopolitanisation processes. As various examples in the case studies show, but what is plausible in general anyway, the further cosmopolitanisation that occurs will have effects on the affordance structures, for example by creating new actors, or reinforcing (or weakening) the position of existing actors. To use an increasingly popular concept, it is a process of co-evolution of technology, technological knowledge and institutions and patterns.[2]

This idea links up with the point made in Chapter 1 (section 1.2.1) and Chapter 2 (section 2.3.3, at the end) that it is the whole array of affordances which shapes the space for cosmopolitanisation. The mix of affordances in this array is dynamic, and co-evolves with cosmopolitanisation. For example, local-cosmopolitan divisions of labour in knowledge production and use evolve over time because of emerging and stabilising roles of intermediary actors. Earlier in this section, I have tried to separate out some of the strands in this fabric. Here, in discussing secular change as a complex affordance, we have to look at the whole fabric.

The co-evolutionary patterns visible in this fabric can be thought of as an 'emplotment' in which different elements and processes become linked up in an overall 'logic'. The notion of emplotment derives from narrative analysis, and has been used by White (1978) and others to understand historical processes.[3] Actions and interactions build on each other and create irreversibilities, which add up to a storyline. For instance, once intermediary actors emerge, they will (try to) continue to play a role in further developments, and actors will take the presence and role of intermediary actors into account in their strategies. A self-reinforcing dynamic emerges as some elements are reinforced and others are excluded. This creates a "logic". Compare also my earlier discussion of Elias' (1978) (in section 1.2.4) two-level dynamic as unintended outcome of interweaving processes. Cosmopolitanisation then appears as the unintended outcome of increasing interweaving under the influence of an evolving affordance structure. Cosmopolitan knowledge, coupled with its reproduction in local practices, becomes part of interweaving.

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[2] See Nelson (1994) and Rosenkopf and Tushman's (1998) article with the interesting title: 'The coevolution of community networks and technology: lessons from the flight simulation industry'. It is now also used for macro-level changes as in long-wave theory (Freeman and Louçã, 2001).

[3] The introduction to his collection of essays, in which White (1978: 15-23) discusses E.P. Thompson's history of the English working class, can be read as a description of how the historian emplots developments to create a comprehensible and memorable story, which reflects the emplotments created by the actors and their interactions themselves, and makes the sequence understandable.

Although I call it a logic, it is not universal but is created in and through emplotment. Actors contribute to emplotment, and to some extent they become prisoners of it. By recognising the process for what it is, they can also become reflexive about it and identify possibilities to modulate it, also to further cosmopolitanisation.

In fact, the picture I drew in section 8.2.5 of cosmopolitanisation as occurring in four phases with transitions from one to the other is itself an emplotment, i.e. a story, told by the analyst, but building on the emplotments that occur out there. Thus, in the same way that I discussed, in Chapter 3 (section 3.3), the creation of a story for each of the case studies, I now created a story across the cases, promising insight transcending the specifics of each of the cases. I am willing to claim that this four-phase sequence will be applicable to every case of technological knowledge becoming more or less translocal, even if secular changes will make the details of the sequence different in different periods of time.

One difference that I touched upon already is how developments (co-evolution) can become reflexive. I made this point already in section 1.3, at the end. Increased reflexivity of the system occurs in the idea of a knowledge society and attempts to consciously work toward it. A specific type of reflexivity would be the recognition of the importance of particular transition mechanisms, through experience or because of reading my analysis, which could then be employed to stimulate a desired transition. A case in point would be my analysis of the importance of demanding actors, in particular for the transition to the translocal phase. Knowing this, actors might make strong demands, not because they needed such performance and reliability, but because they wanted to shift knowledge production to a cosmopolitan level.

Since my case studies together cover a long period, from the late nineteenth century to the end of the twentieth century, I must be able to see some long-term changes as they occur. Reflexivity, in the small and in the large, is only one of them. There appear to be three sets of changes, succeeding each other but obviously not clearly separated.

The first set of changes was discussed already in Chapter 1 (section 1.3). An overall secular change was the rise of bourgeois-professional-industrial society in the nineteenth century. At the meso-level of groups and institutions, one sees professional engineering emerge with its dual goal of acquiring status and extending and improving engineering knowledge. Linked to this, and to bourgeois society, was the rise of "school culture" which meant that practitioners were trained with general insights and methods (which provided incentives for them to work towards cosmopolitanisation). Industrialisation affected the way knowledge was produced because of new requirements (e.g. repeated performance), but also through standardisation sometimes linked to rationalisation. Management structures changed because of different structures of the firm (Chandler, 1977) and to some extent also because of ideals of scientific management and efficiency. These were not immediately applied to industrial research, though (Boersma 2002). What is also visible from the late nineteenth century onward is an increasing involvement of national governments in science and technology, with transitions after the First World War and eventually also the Second World War.

The second set of changes are all linked with what has been called the high tide of modernisation, prepared in the earlier period but coming into its own after the First World War. The historians and sociologists who are writing the history of technology in the Netherlands identified features like the second industrial revolution and its aftermath with the emergence of large technical systems, increasing knowledge intensity, the emergence of a consumption society, big companies with divisional structures, and an interventionist state, increasing technical and socio-technical entanglement and networking, and, as a reaction, attempts at increasing technical and organisational control[4] (Schot *et al.*, 1998), Freeman and Louçã (2001) identify an extended long wave from the 1920s until the 1970s.

While many authors appear to agree that there is a transition located in and around the 1970s, it is not quite clear what kind of transition it is. The new set of secular changes is perhaps easier to identify, even if one runs the risk of projecting one or another trend out of proportion. In the case study of paint, the strong effect of health, safety and environmental considerations was visible which can be linked with what has been called the rise of the Risk Society (Beck, 1992). In the case study of air traffic control, the trend towards a centralised architecture was counteracted (partly because of new possibilities of information and communication technology) by the attempt to develop a more distributed architecture where pilots could have "Free Flight" because of sophisticated infrastructures. Especially this last feature has been identified by other authors as the rise of networks and distributed management. Thomas Hughes (1998) has attempted to trace its emergence since the 1960s, and coined the term 'postmodern technology' to capture what he sees as a major change.

As a conclusion to his book he offers a table (Hughes, 1998: 305) which I can use to capture features of the second and third set of secular changes. With the proviso, as Hughes (1998: 304-5) phrases it: "Characteristics of project and postmodern technology and management can be contrasted with characteristics of modern technology and management. The polarities that follow are too sharply drawn to accord with reality, but the contrasts suggest the differing management and engineering styles."

Clearly, cosmopolitanisation in late-modern societies will be different from the process as it happened earlier. For one thing, actors will be more reflexive, and cosmopolitanisation will be actively anticipated. The emergence of "systems of innovation" with generic "technology infrastructure" already shifted the actor constellations.

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[4] See Beninger (1986) on the "control revolution" in twentieth century.

Table 8.5 Modern and postmodern technology and management (Hughes, 1998: 305)

Modern	Postmodern
production system	project
hierarchical/vertical	flat/layered/horizontal
specialization	interdisciplinarity
integration	coordination
rational order	messy complexity
standardization/homogeneity	heterogeneity
centralized control	distributed control
manufacturing firm	joint venture
experts	meritocracy
tightly coupled systems	networked system
unchanging	continuous change
micromanagement	black-boxing
hierarchical decision making	consensus reaching
seamless web	network with nodes
tightly coupled	loosely coupled
programmed control	feedback control
bureaucratic structure	collegial community
Taylorism	systems engineering
mass production	batch production
maintenance	construction
incremental	discontinuous
closed	open

Still, I contend that the four phases of cosmopolitanisation will remain recognisable as an underlying structure, or better, as an emplotment that is unavoidable given the nature of technological knowledge which its essentially local characteristics — to get a configuration to work — , and the thresholds, epistemic as well as social, economic and political, that have to be overcome. The sequence of experiences, testing, comparisons and parameter-based generalisation, technical model and calculations and simulations remains, even when R&D is given an intrinsic role. As I could show in the case of video recording, R&D is employed to try and create an artefact that has the expected performance. Alternatively, new effects may be thrown up in laboratory research, for example in nanotechnology, which create expectations about possible performance. To exploit these, however, the main sequence has to be followed, even if there can be shortcuts.

It should be added, however, that this is all about industrial technology. Things might work out differently in medical and health, and in agriculture, where man and nature introduce an irreducible variability. One cannot normalise and standardise people (even if there are some attempts), nor is it sustainable to standardise nature. It is possible to restructure the land so that it is uniform almost similar to experimental plots, as has happened for example in the Netherlands, but by now fertility and environmental problems appear. I will take up this issue in the next section.

Looking back at the analysis in this section, what are the main points, in addition to what I have just said about the continuing applicability of the four-phase development pattern? A basic point that needs to be underlined here is that in spite of modernist claims, epistemic progress is not a necessary thing, or in other words, not a sufficient explanation that it occurs. If, when and how it occurs depends on actor-strategies in contexts and their outcomes. This was clear in the case studies, and could be conceptualised and understood further with the help of affordance structures.

To relativise the idea of epistemic progress does not imply that the notion of valid knowledge is relativised. The four phases in the storyline are defined in terms of epistemic scope, and the kind of validity that goes with it. What I do claim is that validity on a cosmopolitan level need not imply validity on the local level, with its local specificities (cf. Chapter 2).

The precarious emergence of technological regimes and collective knowledge reservoirs, my point of departure for this study, depends on the achievement of epistemic translocality. This is a broader concept than the transformation of tacit into codified knowledge. This distinction is often foregrounded in economic and knowledge management literatures (cf. Cowan and Foray, 1997; Nonaka and Takeuchi, 1995), but is a secondary phenomenon, if only because codification of knowledge can still remain local.

Similarly, communication and sharing of knowledge (“openness”) do not capture everything that happens, and has to happen for the emergence of a collective knowledge reservoir. While sharing, and the attendant issues of appropriability of intellectual property rights are obviously important, again it is secondary. Technological knowledge has to be made mobile and transferable before it can be communicated and shared.

8.3 Discussion and implications

The question of the scope of my findings also depends on how I arrived at them. My research object is a complex and evolving phenomenon. Following Giddens’ (1984) example of structuration theory, I took it that the emergence of structures (the transition from fluid to specific, from hot to cold) cannot be understood with a causal factor-type explanation. Indeed, emergent situations are much more difficult to understand than stable situations and require a processual explanation. An explanation in terms of evolving affordance structures is needed, in which affordances are relational and functional aspects of the situation which frame, but not determine, possibilities for action and interaction in the production of knowledge.

Explaining emergent processes with affordances turned out to be not straightforward, and it probably should not be. It is the whole array of affordances which counts, as well as how these are met by actor strategies. To find patterns, one has to look for emerging emplotments in which affordance structures co-evolve with cosmopolitanisation processes.

Despite all the complexities and differences in the case studies, phases and transitions could be identified and generalised, and offer a possibility to disentangle the dynamics. Cosmopolitanisation is not a linear process from less to more. The storyline in emplotments of cosmopolitanisation is one of phases and transitions between phases. And as I noted already at the end of the preceding section, such a story is not something the analyst projects on the dynamics, but reflects a storyline which is created by actors themselves.

With regard to the specification of cosmopolitanisation as a socio-cognitive structuration process in which translocal knowledge is produced, supported by an infrastructure and carried by a local-cosmopolitan division of labour, I can conclude that this specification proved to be adequate and sufficiently general to cover the broad range of technologies studied in this thesis. It can be used to study institutionalisation processes in technological domains, even if it is not certain, as I noted already, whether in other domains than those of industrial technology the same phased process will be visible. Before I briefly address this point, I note that this approach offers a valuable addition to general social theory which is not geared to technology. In particular (and not only in social theory), translocality of technological knowledge is taken for granted, while I emphasised that this it not obvious. In terms of Giddens' structuration theory, the disembedding of technological knowledge requires cognitive work, infrastructures and local-cosmopolitan divisions of labour.

When I gave, in Chapter 1, an overview of social theories and some theories of industrial dynamics, the idea was that, in principle, insights from general social theory should be applicable to technological domains. However, it turned out that additions are required. The fact that institutionalisation of technological knowledge implies that knowledge has to be made translocal before it can become part of "techno-structuration" (as Rammert (1997) phrased it) has to be taken into account. A further point, and an interesting finding from the case studies, is that cosmopolitanisation contributes to cooling off of technological domains and the emergence of technological regimes. The actual dynamics combine actor strategies, evolving actor-constellations and epistemic transformations in a phased process. Irreversibilities are created this way, and reinforced by the emergence of a cosmopolitan level (a special case of the general two-level situation as discussed by Elias (1978) in his figuration theory, cf. section 1.2.4). Actors at the second level are involved in the production of translocal knowledge as such which is (hopefully) taken up at the lower level.

These are general considerations. Cognitive and material and social work is always necessary to create translocal knowledge and a division of labour including a cosmopolitan level, but the nature of the work, and thus perhaps the phases and the dynamics of transition may be different when it is not about nuts and bolts, so to speak, but about medical interventions in humans, or about agriculture as a transformation of nature.

In the medical and health sector, there has been a long tradition of experience-based knowledge, which remains important in the clinic. There was also a tradition of tinkering with technologies promising diagnosis (as with Röntgen rays) or therapy (as with electrotherapies around 1900). These stories are now being told by historians, and with attention to the movement towards translocal knowledge (Hessenbruch 2000, Houwaart 2001). With the so-called scientification of medicine, an impression is created that local knowledge has disappeared. As a reaction, the continuing importance of clinical judgement and contextual understanding of general practitioners is sometimes emphasised. A closer look at what happens when the possibility of a new medical intervention is mooted shows that, in fact, almost the same phases occur as I reconstructed for industrial technological knowledge.[5]

In-vitro fertilization (IVF) started out as an idea tried out by medical doctors in England and Australia, with very little understanding of how (and why) it could work, and be made to work. There was competition to be the first, and some exchange of knowledge to be able to strategically position oneself and the others. The breakthrough occurred in 1978, when baby Louise Brown was born after IVF-treatment by Edwards and Steptoe in Oxford. IVF was then tried out in many countries. Australian IVF doctors gave a course in Rotterdam, which led to clinical work on IVF in Rotterdam and elsewhere in the Netherlands. There were many uncertainties, and the protocols that were drawn up had no basis in robust knowledge. By the late 1980s, governments intervened, and guidelines were set up to limit IVF-treatment to certified practitioners. Professional societies of obstetricians and gynaecologists started to collect data and experiences to create better protocols and indications; in other words, a translocal phase had arrived.

In IVF, as well as for medical interventions in general, there is now a conscious effort to create robust translocal knowledge in the movement for evidence-based medicine, visible in the Cochrane Collaboration, in policy measures and in the work of advisory bodies. Consensus conferences to explore shared and hopefully authoritative protocols are held, and their results feed into local practices, directly or after an official body promulgates protocols and guidelines. Interestingly, second thoughts are now being voiced about the insufficiency of the general prescriptions of evidence-based medicine in local situations (Van Crevel 1996).

In the agricultural sector, locality was and remains of overriding importance: production has to be realised by tending and transforming nature on the spot.[6] The vicissitudes of weather, soil, plants and animals imply high uncertainties, and this shared fate afforded exchange of experiences and learning, up to collective invention (Allen's (1983) term, but now not limited to private firms in industry). High variability of circumstances and outcomes, and the necessary local focus, implied that there was little affordance to go further than an interlocal phase (the fact that there were many small farmers contributed to this), and also that it was almost irrelevant to try and develop translocally valid knowledge.

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[5] I am grateful to Marta Kirejczyk, University of Twente, for sharing her knowledge about medical practices and in particular in-vitro fertilisation with me.

[6] My discussion of the agricultural sector is based on inputs from Arie Rip (University of Twente).

Even so, traditional agriculture shows some major achievements, for example in socio-technical irrigation systems.

Secular changes were visible from the eighteenth century onwards, with agricultural reform movements driven by Enlightenment ideas as well as big land-owners wanting to improve their exploitation of the land, and the peasants. In the nineteenth century, artificial fertilizers and later, mechanisation, transformed agricultural practices and created an opportunity for separate knowledge production, say about chemical fertilizers and their use, which then had to be disseminated to the farmers. The establishment of agricultural extension services (from the late nineteenth century onwards) institutionalised this projected division of cognitive labour. It was a projected division, because it was not related to experience-based knowledge of farmers and its aggregation. Such knowledge was considered to be traditional, and in need of replacement. In this way, an agricultural "expert system" (Giddens' term, as elaborated for agriculture by Van der Ploeg (1999)) emerged and became dominant, first in Western countries, and then, on the coat tails of colonisation and later, development aid, in developing countries. In other words, the local-cosmopolitan division of labour in the technological regime was heavily biased to import from laboratory-based and experimental-plot-based research to a wide variety of localities.

Implications

Among the various possible implications of my findings, as summarised at the end of section 8.2, I shall focus on the way companies try to manage knowledge processes and the way governmental agencies try to stimulate knowledge production and uptake in (national) innovation systems. These are recent phenomena, and indicators of how reflexive developments have now become. My concern is about the quality of the reflexivity.

Technological knowledge production has become recognised as a vitally important asset for individual businesses as well as for national industries and national innovation systems. The rise of literature on knowledge management signals the interest of businesses in knowledge production and maintenance. National innovation systems theory has been picked up in policy circles to find ways to stimulate the production and dissemination of knowledge within (national) industries.

On the level of individual firms, knowledge management has become popular in the 1990s (e.g. Nonaka and Takeuchi, 1995). Knowledge management focuses on how firms can get the most out of the knowledge and experience of their employees. Its central question is how existing tacit knowledge can be transferred to other actors within a firm, or within business networks. It is argued that knowledge has to be made communicable. While it is recognised that knowledge needs to be decontextualised "so that it can be explicitly represented and leveraged in a range of settings" (Millar *et al.*, 1997), in practice this epistemic challenge is reduced to the question how to structure the data bases.

There are more interesting approaches. In Nonaka *et al.* (2000), knowledge creation within firms is conceptualised with the notions of the so-called SECI process and 'Ba'. SECI is the cycle (spiral) of socialisation (which means that tacit knowledge is transferred in interactions within a team of 'field'), externalisation (which means that tacit knowledge is articulated and transformed into explicit knowledge by using models, metaphors and analogies), combination (which means that explicit knowledge is converted into more complex and systematic sets of explicit knowledge through interaction) and, finally, internalisation (which means that explicit knowledge is integrated in tacit knowledge by sharing explicit knowledge within groups). Ba roughly means 'place that offers a context'. It combines a 'here and now' quality with the boundedness of a shared context, and the energy imparted to participants in Ba. While it can be stimulated and organised as a dedicated arrangement (environment), it is flexible, even fleeting. The context is dynamic as it is redefined through the actions. The combination of SECI process and Ba allow an organisation to create, and profit from, organisational learning. The goal of knowledge management is to realise practical benefits of tacit knowledge held by individuals through externalisation and amplification which can be achieved through dynamic interactions between all four modes of knowledge conversion.

While such an approach to knowledge creation has its value, two remarks can be made. Knowledge management focuses on the transition from tacit to explicit (and vice versa). As I argued before, this transition is secondary while the transition from local to translocal is primary. In particular when knowledge creation and sharing occurs in inter-organisational settings, the narrow focus on codification should be broadened by an emphasis on translocality. Secondly, knowledge creation does not only occur within organisations but also on a collective level. Companies are part of industries and there will also be knowledge processes at a collective level, depending on the phase of cosmopolitanisation the technology is in. Thus, management of technological knowledge should take into account the emergence of local-cosmopolitan divisions of labour, and how firms can become part of it, benefit from it, contribute to it, and become guided by it. In other words, knowledge management should not only focus on intra- or inter-organisational knowledge processes, but it should also take into account that knowledge production can occur on a cosmopolitan level, and that different phases have different implications for how businesses should manage technological knowledge production.

The fact that companies are part of an organisational field and that this affects knowledge production is recognised by some authors, although the emergence of a cosmopolitan level is not. For instance, Nonaka *et al.* (2000) note that

> "the knowledge-creating process is not confined within the boundaries of a single company. The market, where the knowledge held by companies interacts with that held by customers, is also a place for knowledge creation. It is also possible for groups of companies to create knowledge. If we further raise the level of analysis, we arrive at a discussion of how so-called national systems of innovation can be built. For the immediate future, it will be important to examine how companies, governments and universities can work together to make knowledge creation possible."

What we see here is that the more interesting approaches to knowledge management identify challenges which are being addressed by other types of actors already. To build innovation systems is taken up in innovation policy of national governments. In fact, the notion of a dynamic innovation system has become a central element in policy. Interaction, collaboration and knowledge exchange are foregrounded. A recognised bottleneck in the innovation systems is the diffusion of knowledge from public knowledge institutes to industry. This is why governments stimulate collaborations between these groups. The role of bridging or intermediary organisations in the transfer of knowledge from public knowledge institutes and industry is recognised.

The concept of cosmopolitanisation is a necessary addition to the way policy makers address this problem of knowledge utilisation by industry. Transfer of knowledge from universities to industry depends on the level of cosmopolitanisation that is achieved within a technological domain. If innovation policy aims to increase utilisation of knowledge produced at universities, it should focus on trying to make universities part of a local-cosmopolitan cognitive division of labour, and thus increase cosmopolitanisation. In emergent situations governmental agencies can try to modulate and induce affordance structures. The case study of paint suggested that involvement of universities in a cognitive division of labour became effective after the government had modulated the affordance structure by becoming a demanding actor itself. Thus, interaction, collaboration and knowledge exchange within systems of innovation can be stimulated by inducing cosmopolitanisation by modulating the affordance structure and providing infrastructures for circulation and aggregation.

In started this thesis with a discussion of Giddens' structuration theory and his ideas about modernisation. Modernisation in his view is characterised by increasing time-space distanciation. "Expert systems" are important disembedding mechanisms as they produce knowledge which is context-independent and can be used across wide tracts of time-space. This study has shown that cosmopolitanisation and modernisation are entangled. On the one hand, cosmopolitanisation increases time-space distanciation in technological domains, while on the other hand modernisation creates affordances for (further) cosmopolitanisation. In terms of structuration theory: cosmopolitanisation is both the outcome and the medium of modernisation in technological domains.

I already noted that Giddens' theory of modernisation was too general and abstract to address the question of how technologies are cosmopolitanised. My recurrent argument has been that in social theory the precariousness of the achievement of translocality in technological domains is overlooked. I can now add some further comments on how Giddens addresses the consequences of modernisation. Modernisation reinforces globalisation which results in the fact that an increasing number of people and practices become structured by disembedded institutions. This has positive consequences because its offer new opportunities for disempowered groups. On the other hand, globalisation also means that local practices lose their local embeddedness. Globalisation incites resistance, as is visible in recent demonstrations from ‘anti-globalists’. Thus, the relation between the local and the global is ambiguous.

In the realm of technology, cosmopolitanisation can result in similar ambiguities between the global and the local. The cosmopolitan level can ‘colonise’ the local practices. This might have negative consequences as cosmopolitan technologies are not geared to specific local circumstances. Technology transfers to Third World Countries, for instance, often have been problematic. However, in case of technology this negative consequence of modernisation is inherently limited. The achievement of cosmopolitan knowledge in technological domains is more precarious than in other social domains. In the end, technologies have to work and cosmopolitan knowledge can not simply be imposed upon local practices. The malleability of local practices is limited, if only because there are material and physical constraints. Indeed, technological regimes depend on constructive combinations of local and cosmopolitan. The cosmopolitan, global level and the local level mutually dependent. Thus, paraphrasing the title of this dissertation, cosmopolitanising technologies leads to “glocal” technologies.

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Samenvatting

Kenmerkend in de ontwikkeling van technologische domeinen is dat er een gedeeld kennisreservoir kan ontstaan. Voorbeelden van zulke gedeelde kennis zijn handboeken, technische standaarden en technische modellen. Het punt van vertrek voor dit proefschrift is dat het gedeeld raken van technologische kennis in een collectief reservoir – de essentiële stap in het ontstaan van zgn. Technologische regimes – niet vanzelfsprekend is omdat technologische kennis in beginsel lokaal ontstaat en gearticuleerd en gedecontextualiseerd moet worden om deelbaar te worden. Met andere woorden, technologische kennis die in een bepaalde locatie is ontwikkeld kan niet zo maar worden overgedragen naar een andere locatie. Kennis moet eerst *translokaal* gemaakt worden, d.w.z. voldoende generiek en contextvrij. Dit vergt allerlei inspanningen en dus kosten, en het is niet vanzelfsprekend dat actoren hierin willen investeren. Een gedeeld kennisreservoir heeft namelijk kenmerken van een collectief goed waarvan anderen kunnen profiteren zonder dat ze er zelf aan bijgedragen hoeven te hebben.

De onderzoeksvragen die in dit proefschrift worden beantwoord zijn: hoe verloopt het proces waarin technologische kennis gedeeld raakt? Kunnen daarin patronen worden onderscheiden? Hoe kan een dergelijk sociocognitief proces worden verklaard?

Als eerste stap op weg naar beantwoording van deze vragen wordt het onderzoeksobject gespecificeerd als een proces van 'kosmopolitanisering' (hoofdstuk 2). Het proces bestaat uit drie onderdelen: (1) het produceren van translokale, *kosmopoliete* kennis; (2) het ontstaan van een arbeidsverdeling met een lokaal en een kosmopoliet niveau van kennisactiviteiten; en (3) het ontstaan van een infrastructuur voor circulatie en uitwisseling van kennis.

Gebruik makend van inzichten uit de sociologie van kennisproductie wordt beschreven hoe door middel van *circulatie* en *aggregatie* lokale kennis wordt getransformeerd in kosmopoliete kennis. Zowel sociale strategieën (o.a. alliantievorming, creëren van vertrouwen en dominantie) als technische middelen (metrologie, instrumentatie, standaardisering) spelen hierin een rol. Lokale kennis zal overigens altijd belangrijk blijven omdat de toepassing van kosmopoliete kennis op locatie recontextualisatie vereist.

Het tweede kenmerk van kosmopolitanisering is dat er gaandeweg een arbeidsverdeling ontstaat met daarin actoren en praktijken die zich specifiek richten op het creëren, onderhouden en verbeteren van een collectief kennisreservoir. Met andere woorden, er ontstaat een extra, *kosmopoliet niveau* van kennisactiviteiten dat niet zozeer gericht is op het oplossen van concrete problemen die zich voordoen in lokale praktijken, maar op het ontwikkelen en bevorderen van locatieoverstijgende kennis. (Dit is overigens een specifieke invulling van het algemene idee zoals beschreven in Elias' figuratietheorie waarin tweelagen-situaties kunnen ontstaan uit steeds complexer wordende interactiepatronen).

Met name intermediaire actoren spelen een belangrijke rol op het kosmopoliete niveau. Zij intermediëren tussen lokale praktijken en/of tussen kosmopoliete kennisreservoirs en lokale praktijken. In de twintigste eeuw is er een breed scala aan intermediaire actoren ontstaan die actief zijn in de productie van translokale kennis. Professionele verenigingen met hun secties en forums zijn een voorbeeld. Andere voorbeelden zijn ingenieursbureaus die zowel een professioneel belang hebben in het produceren van kennis die breed toepasbaar is als in het participeren in kosmopoliete settings om reputatie en zichtbaarheid te vergroten. Ook sectorale onderzoeksinstituten, universitaire onderzoeksgroepen, brancheorganisaties, consortia, overheidsorganen op het gebied van wetenschaps- en technologiebeleid, etc. kunnen onderdeel worden van een lokaal-kosmopoliete arbeidsverdeling. De functie van intermediair is herkenbaar in recente activiteiten als expert consultancy, kennisdelen, kennismakelarij en benchmarking. Intermediaire actoren spelen een cruciale rol in het ontstaan van een infrastructuur van forums, het derde kenmerk van kosmopolitanisering, die mogelijkheden voor interactie en circulatie van kennis bieden.

De tweede stap is het ontwikkelen van een conceptualisering waarmee het proces van kosmopolitanisering kan worden begrepen (hoofdstuk 2). Daarbij wordt gebruik gemaakt van inzichten uit een literatuurstudie van verschillende sociologische theorieën (hoofdstuk 1) waarin het ontstaan van structuren en instituties wordt gethematiseerd (o.a. structuratietheorie, *social rule system* theorie, sociale-netwerktheorie, neo-institutionele theorie, figuratietheorie). In het algemeen geldt dat het verklaren van het ontstaan van structuren die verdere ontwikkelingen sturen niet eenvoudig is. In emergente situaties kan niet gewerkt worden met determinerende causale factoren omdat deze zelf nog in ontwikkeling zijn. Daarom wordt gekozen voor een verklaringsaanpak gebaseerd op *affordances*. Affordances zijn positieve of negatieve suggesties voor en mogelijkheden tot handelen en interactie die in de situatie opgesloten liggen. Een affordance structuur is als landschap met gradiënten waarin sommige routes beter begaanbaar zijn als andere routes. Affordances zijn relationeel, d.w.z. dat ze verschillend kunnen uitwerken voor verschillende actoren.

De affordance structuur voor kosmopolitanisering wordt gekarakteriseerd door drie onderdelen: (1) technologie; (2) actorconstellatie; en (3) de historisch gegroeide infrastructuren en repertoires die, als ze er eenmaal zijn, verdere ontwikkelingen zullen beïnvloeden. Cruciaal voor de technologische component van de affordance structuur is de technische hiërarchie: er zijn materialen, componenten, devices, artefacten en systemen. Zo is de kennis die nodig is om een complex systeem te ontwerpen, te bouwen en te onderhouden heterogener dan de kennis die nodig is om een materiaal te fabriceren. De vier case studies (hoofdstukken 4 t/m 7) bevinden zich op verschillende niveaus in de technische hiërarchie: de *materialen* gewapend beton en verf, de *devices* plus *artefacten* van videorecording, en het *systeem* Air Traffic Control dat zelf weer uit technische systemen, met hun artefacten, devices en materialen, is opgebouwd.

Het tweede onderdeel van de affordance structuur wordt gevormd door de constellatie van kennisproducerende actoren. Daarbij spelen niet alleen actoren in de waardeketen een rol, maar ook intermediaire actoren. De actorconstellatie is een dynamische variabele en is verweven met het ontstaan van een lokaal-kosmopoliete arbeidsverdeling. Gebruikmakend van inzichten uit literatuur over collectieve goederen kan worden gesteld dat het collectieve goed van translokale kennis het moeilijkst tot stand zal worden gebracht in grote, homogeen samengestelde constellaties, en het gemakkelijkst in kleinere, heterogene constellaties. De aanwezigheid van dominante actoren genereert affordances, met name als zij ook een inhoudelijke belangstelling hebben voor de werking en betrouwbaarheid van een technologie. Het concept van innovatiepatronen kan worden gebruikt om te voorspellen welk type actoren een dominante rol kunnen spelen. In *user-driven* innovatiepatronen, bijvoorbeeld, kan verwacht worden dat professionele gebruikers een affordance creëren voor de productie van translokale kennis. Affordances worden ook gegenereerd op het moment dat intermediaire actoren onderdeel worden van de constellatie. Het ontstaan van brancheorganisaties bijvoorbeeld, biedt mogelijkheden voor collectief handelen en kan helpen drempels te overwinnen. Als er eenmaal een begin van een lokaal-kosmopoliete arbeidsverdeling ontstaat, kan er een zelfversterkend kosmopolitaniseringsproces optreden.

Dit sluit aan bij het derde onderdeel van de affordance structuur, de historisch gegroeide setting. Kosmopolitanisering begint altijd in een voorgestructureerde situatie. Bestaande intermediaire actoren die op zoek zijn naar emplooi kunnen bijvoorbeeld proberen een rol te gaan spelen in productie van kennis in opkomende domeinen, waardoor kosmopolitanisering versneld wordt. Voorbeelden van seculiere veranderingen die kosmopolitaniseringsprocessen beïnvloeden zijn de opkomst van professionele ingenieurs en hun vakverenigingen, de opkomst van "school culture" waarin het belang van generieke en abstracte kennis wordt benadrukt en de toenemende bemoeienissen van nationale overheden in wetenschappelijke en technologische kennisproductie. In de twintigste eeuw creëerden seculiere veranderingen een drijvende kracht achter kosmopolitaniseringsprocessen, relatief onafhankelijk van de twee eerder genoemde variabelen.

De eerste case studie (hoofdstuk 4) is gewapend beton en wordt gebruikt als een 'existentiebewijs' voor kosmopolitanisering. Het is een technologie op het niveau van materialen die opkomt in de negentiende eeuw, d.w.z. op een moment dat de wereld nog niet zo vol was met kosmopoliete elementen als in de twintigste eeuw waardoor het verschijnsel in relatief 'zuivere' vorm kan worden getraceerd. Vier fasen kunnen worden onderscheiden. In de eerste fase (1850s-1870s) ontwikkelden en exploiteerden verschillende innovatieve producenten nieuwe combinaties van beton en ijzer als oplossing voor verschillende problemen zoals houtbederf, brandveiligheid en schokbestendigheid. De werking van de technologie was grotendeels onbekend, maar met behulp van trial & error en testen werden technologische en commerciële vorderingen gemaakt. Kennis was en bleef lokaal, niet in de laatste plaats omdat aannemers hun ervaringskennis grotendeels geheim hielden. De technologische affordances waren zwak: de werking was ondoorgrondelijk, voor producenten evenals voor concurrenten. Vanwege de lage mate van complexiteit was afstemming en uitwisseling met andere locaties niet nodig, terwijl mogelijkheden voor standaardisatie beperkt waren door wisselende kwaliteit van grondstoffen en veranderlijke omstandigheden tijdens de uitvoering. Zolang de gewapend-betonconstructies niet te groot waren, bleef het risico beperkt en kon worden gereduceerd door achteraf testen. De actorconstellatie werd gekenmerkt door een aantal kleine producenten die in nichemarkten opereerden.

In de tweede fase (1870s-1890s) werden gepatenteerde “systemen” ontwikkeld door ambitieuze aannemers die probeerden een plek te veroveren in de bouwwereld. In netwerken van patenthouders en licentiehouders werd kennis op meer systematische wijze geaccumuleerd en uitgewisseld waardoor kennis van de verschillende systemen meer robuust werd. Er was sprake van hevige concurrentie tussen verschillende systemen. In toenemende mate raakten professionele klanten zoals Openbare Werken van nationale en gemeentelijke overheden geïnteresseerd. Hierdoor werd het kennismonopolie van de aannemers problematisch omdat deze klanten geen technologie wilden toepassen die ze zelf niet konden berekenen. Als het ging om grote constructies en woningbouw moest het risico op instorting zoveel mogelijk *vooraf* worden gereduceerd door middel van het opstellen van betrouwbare berekeningswijzen.

In de derde fase (1890s-1910s) werd acceptatie door de bouwwereld een belangrijke drijfveer voor aannemers om delen van hun kennis openbaar te maken en om te participeren in de productie van translokale kennis die acceptabel was voor professionele ingenieurs, d.w.z. kennis die onderbouwd kon worden door theorie en experimentele data. Ingenieursverenigingen met hun tijdschriften en bijeenkomsten werden belangrijke plaatsen voor uitwisseling en productie van kennis. In verschillende landen werden standaardisatiecommissies opgericht die als doel hadden betrouwbare gewapend-betonvoorschriften op te stellen. Een collectief theoretisch-experimenteel project ontstond waaraan zowel aannemers en professionele ingenieurs die werkten voor grote opdrachtgevers en bouw- en woningtoezicht deelnamen. Om hun reputatie en zichtbaarheid te vergroten publiceerden ambitieuze aannemers handboeken en ontwikkelden berekeningswijzen om de sterkte vooraf te kunnen berekenen. Tegelijkertijd werd gewapend beton opgenomen in curricula van technische universiteiten waardoor een nieuwe generatie ingenieurs vertrouwd raakte met de technologie. Met het ontstaan van specialistische tijdschriften werd de infrastructuur in toenemende mate gedifferentieerd. Aannemers richtten brancheverenigingen op om op die manier een grotere rol te kunnen spelen op het kosmopoliet niveau.

In de vierde fase (1920s-heden) ontstonden ‘normale praktijken’ die werden georiënteerd door gestandaardiseerde, kosmopoliete kennis. Aannemers begonnen in toenemende mate te participeren in collectief onderzoek. Met name na de Tweede Wereldoorlog, mede onder invloed van seculiere veranderingen waarin industrialisatie, rationalisatie en standaardisatie kernbegrippen waren en er een grote behoefte aan snelle en goedkope bouwtechnieken was vanwege de Wederopbouw, ontstonden verschillende nieuwe intermediaire actoren die zich richten op collectief onderzoek. De lokaal-kosmopoliete arbeidsverdeling werd hierdoor verder versterkt en uitgebreid.

Naast het existentiebewijs (er treedt kosmopolitanisering op) is er dus een tweede resultaat: de suggestie dat het verloop van kosmopolitanisering gekarakteriseerd kan worden door een vierfasen schema: respectievelijk een lokale fase, een interlokale fase, een translokale fase en een kosmopoliete fase. In de lokale fase is kennis grotendeels lokaal. In de interlokale fase nemen onderlinge afhankelijkheden toe en is er sprake van toenemende circulatie. In de translokale fase wordt voor het eerst expliciet kennis ontwikkeld die niet gericht is op het oplossen van concrete problemen in lokale praktijken, maar die gericht is op het verbeteren van (het begrip van) de technologie als zodanig. In de kosmopoliete fase is er sprake van een *reversal* waarin translokale kennis geïnstitutionaliseerd raakt en onderdeel wordt van een richtinggevend collectief kennisreservoir. Deze suggestie wordt als kader voor de volgende case studies gebruikt, en daarmee ook op de proef gesteld.

Terwijl verf (hoofdstuk 5) net als gewapend beton een technologie op het niveau van materialen is, was het verloop van kosmopolitanisering veel langzamer. Niettemin kan eenzelfde gefaseerd patroon worden geïdentificeerd. Verf is een eeuwenoude technologie. Tot en met de negentiende eeuw bleef het echter een lokale technologie in de zin dat er nauwelijks sprake was van een kosmopoliet niveau waarop kennis over verfformulering als zodanig werd ontwikkeld. Circulatie van formuleringskennis werd beperkt omdat formuleerders hun ervaringskennis geheim hielden. Tegelijkertijd waren er wel experts die handboeken schreven met daarin recepturen. De affordances waren zwak, onder meer omdat de technologie niet complex en niet risicovol was. Aan het begin van de twintigste eeuw bestond de actorconstellatie uit vele kleine, regionaal opererende verffabrikanten met hun eigen klantenkring. Met de intrede van machines voor verfproductie en de opkomst van grote industriële klanten die coatings wilden met een uniforme kwaliteit ontstonden er affordances om te investeren in formuleringskennis. Verffabrikanten begonnen met het opzetten van laboratoria om de kwaliteit van verf te meten. Kennisproductie bleef overigens empirisch.

Na de Eerste Wereldoorlog ontstond een interlokale fase waarin fabrikanten begonnen samen te werken in reactie op het beschikbaar komen van nieuwe verfstoffen door de chemische industrie. Brancheorganisaties maakten collectief onderzoek mogelijk. In Engeland werd met subsidie van de overheid een *Paint Research Association* opgericht die het begin markeerde van een lokaal-kosmopoliete arbeidsverdeling. Gedurende de twintigste eeuw zouden soortgelijke onderzoeksinstituten ook in andere landen worden opgericht, deels als een gevolg van een brede erkenning van het belang van industrieel onderzoek. Brancheorganisaties begonnen met het organiseren van cursussen om professionalisering te stimuleren. Als gevolg van fusies en overnames veranderde de actorconstellatie en ontstonden gaandeweg grote verffabrikanten met meer middelen voor onderzoek. Tegelijkertijd bleef het meeste onderzoek gericht op het leren omgaan met nieuwe synthetische verfstoffen en het oplossen van praktische problemen. Onder invloed van nieuwe regelgeving vanaf de jaren '80 gericht op verminderen van schadelijke effecten van oplosmiddelen werd de verfindustrie gedwongen om nieuwe verfsystemen te ontwikkelen. Dit vormde een aanleiding om meer fundamenteel onderzoek te gaan doen naar de werking van verf als zodanig. De notie van *paint engineering* kwam in gebruik. Universitaire onderzoeksgroepen werden betrokken in het modelleren van verf. Dit was het begin van een translokale fase waarin een meer verregaande lokaal-kosmopoliete arbeidsverdeling ontstond die gericht was op het ontwikkelen van een kosmopoliet kennisreservoir. Als de kennis die op het kosmopoliet niveau ontwikkeld wordt daadwerkelijk richtinggevend wordt voor lokale praktijken, zal dat het begin zijn van een kosmopoliete fase.

Er is een opmerkelijk verschil in tempo van kosmopolitanisering tussen de twee cases. De aanwezigheid van dominante klanten met een inhoudelijke belangstelling voor de werking van een technologie en die veeleisend zijn in termen van berekenbaarheid van de technologie, is blijkbaar een belangrijke voorwaarde voor verdere ontwikkeling. Hiermee samenhangend is het verschil in risico: bij gewapend beton was de prikkel om onzekerheid *vooraf* te reduceren groter dan bij verf.

Het verloop van kosmopolitanisering in het geval van videorecording (hoofdstuk 6) werd voor een deel bepaald door een historisch gegroeide context die was voorgestructureerd door uitkomsten van voorafgaande kosmopolitaniseringsprocessen. Zo was er van begin af aan een professionele technische gemeenschap met een kosmopoliete dimensie en speelden industriële laboratoria van grote bedrijven een belangrijke rol in kennisproductie. In de jaren '50, toen de verwachting dat videotaperecording mogelijk moest zijn breed gedeeld raakte, was er een kosmopoliet kennisreservoir op het gebied van geluidsopname- en televisietechnologie waarop voortgebouwd kon worden. Hierdoor was er geen lokale fase zoals in de vorige twee casestudies. Er ontstond een racedynamiek waarin verschillende producenten verschillende varianten ontwikkelden. Deze interlokale fase werd afgesloten toen Ampex in 1956 als eerste een werkend prototype kon demonstreren dat enthousiast werd onthaald door televisiestudio's. In de translokale fase werd deze zgn. *Quadruplex* een dominant design. Het prototype werd verder ontwikkeld tot een robuust artefact waardoor interoperabiliteit mogelijk werd. Kennis raakte gedeeld dankzij productdemonstraties, presentaties op conferenties, publicaties in vaktijdschriften, patenten, uitwisselingen in het kader van cross-licensing overeenkomsten, joint ventures en door *reverse engineering* door concurrenten. Broadcasters en producenten werkten samen in een standaardisatiecommissie om standaarden en *recommended practices* te ontwikkelen. In de jaren '60 en '70 werd de *Quadruplex* een gestandaardiseerde en kosmopoliete technologie. Het relatief snelle verloop van kosmopolitanisering kan worden verklaard door sterke affordances vanuit technologie (o.a. interoperabiliteit), actorconstellatie (relatief weinig kennisintensieve producenten en professionele klanten), en de voorgestructureerde setting.

Een soortgelijke dynamiek ontstond toen in de jaren '60 werd geprobeerd een videotaperecorder voor de consumentenmarkt te ontwikkelen. De verwachting dat het mogelijk moest zijn werd breed gedeeld en verschillende partijen ontwikkelden varianten. Doelstellingen in termen van prestatie, prijs, formaat, gebruikersgemak, etc. bleken moeilijk haalbaar. Zolang onduidelijk was wie de race zou kunnen winnen weigerden producenten interoperabiliteitsstandaarden af te spreken. Een translokale fase begon toen overgebleven bedrijven allianties begonnen te sluiten om de kans op technologisch en commercieel succes te vergroten. In wisselende allianties werd kennis uitgewisseld en de overgebleven varianten hadden een vergelijkbare basisconfiguratie. De strijd om wie de *industry standard* zou zetten werd uiteindelijk gewonnen door JVC's VHS format. De uiteindelijke videocassetterecorder was het resultaat van ruim 20 jaar ontwikkeling waaraan vele partijen een bijdrage hadden geleverd. Een groot deel van de kennis inmiddels werd gedeeld binnen de industrie.

Opmerkelijke verschillen in de affordance structuur in vergelijking met voorgaande casestudies is de voorgestructureerde context waarin videorecording ontstond. Vanaf het begin was er al een kosmopoliet niveau en een uitgebreide infrastructuur waarop voortgebouwd kon worden. De technologische affordances waren sterker vanwege de mogelijkheid van *reverse engineering*, de hogere mate van complexiteit, het belang van herhaalbare, uniforme en betrouwbare performance en de inpassing in bestaande televisiesystemen. De actorconstellatie genereerde affordances vanwege het beperkte aantal grote kennisintensieve spelers en de aanwezigheid van professionele verenigingen en brancheorganisaties met hun forums voor uitwisseling en standaardisatie.

Air Traffic Control systemen (hoofdstuk 7) zijn zeer complexe systemen waarin verschillende subsystemen voor communicatie, navigatie en surveillance tezamen veilig en efficiënt vluchtverkeer mogelijk moeten maken. In de lokale fase voor de Tweede Wereldoorlog waren ATC systemen losjes gekoppelde configuraties waarin *'humanware'* een belangrijke rol speelde. Een interlokale fase ontstond na de oorlog toen internationale interoperabiliteit een belangrijke eis werd vanwege de opkomst en groei van internationaal luchtverkeer met straalvliegtuigen. Standaardisering gebeurde op het niveau van subsystemen en niet op het niveau van de overall architectuur. De "modernisering" van ATC systemen verliep in opeenvolgende generaties van steeds complexere en meer geïntegreerde nationale systemen. Elke nieuwe generatie moest voortbouwen op historisch gegroeide systemen om een soepele transitie mogelijk te maken. Toen in de jaren '80 ATC systemen overbelast dreigden te raken werd er door de transnationale organisatie ICAO een ATC architectuurconcept ontwikkeld dat richtinggevend moest worden voor de nieuwe generatie nationale ATC systemen. Er ontstond een translokale fase waarin het zgn. CNS/ATM concept een *guiding principle* werd, relatief onafhankelijk van de historisch gegroeide systemen. Er ontstond een kosmopoliet niveau waarop werd samengewerkt door nationale en transnationale organisaties (bijv. Eurocontrol) om een wereldwijde, geïntegreerde systeemarchitectuur te ontwerpen. *Systems engineering* organisaties speelden een belangrijke rol op het kosmopoliete niveau, evenals grote internationaal opererende bedrijven die waren overgebleven na een proces van fusies en overnames.

De hoge mate van complexiteit creëerde een sterke affordance voor productie van kosmopoliete kennis om zodoende interlokale coördinatie te vergemakkelijken en de beheersbaarheid te vergroten. Anderzijds maakte de uniekheid en specificiteit van ATC systemen het leren en overdragen van kennis problematisch. De noodzaak om het risico op ongelukken zoveel mogelijk te verkleinen creëerde affordances voor betrouwbare en overdraagbare kennis. Overheidsorganisaties voor de luchtvaart en hun technische consultants speelden een belangrijke rol in de actorconstellatie.

De suggestie dat het verloop van kosmopolitanisering gekarakteriseerd kan worden door een patroon van vier fasen is versterkt. Een belangrijke constatering is dat het hierbij niet gaat om een lineair verloop van weinig naar veel kosmopolitanisering, maar om een niet-lineair proces met drempels en transities. De cruciale transitie is die van interlokaal naar translokaal als kennis wordt geproduceerd relatief onafhankelijk van specifieke lokale contexten. Toenemende eisen aan de betrouwbaarheid en berekenbaarheid van de performance spelen een belangrijke rol in deze transitie. Hoe dit verloopt, en wat de vervolgstappen zijn, hangt af van de overall affordance structuur. De transitie naar de kosmopoliete fase wordt gekenmerkt door institutionalisering en standaardisering waardoor dominante regels ontstaan. Terwijl handelingen op het kosmopoliete niveau in de translokale fase *ad hoc* zijn, zijn ze in de kosmopoliete fase structureel geworden.

In de casestudies werden technologische componenten van de affordance structuur—complexiteit, belang van herhaalbare performance, risico en het wel/niet onderdeel zijn van een ‘megamachine’ — getraceerd. Aanvullende inzichten zijn dat affordances niet altijd in dezelfde richting hoeven te werken. Een hoge mate van complexiteit, bijvoorbeeld, creëert enerzijds een affordance voor lokatieoverstijgende kennis, maar wordt tegelijkertijd tegengewerkt door de uniekheid en specificiteit die kenmerkend is voor een complexe technologie. Ook is gebleken dat het belang van herhaalbare performance op zichzelf een onvoldoende krachtige affordance is voor de productie van translokale kennis omdat kennisproducenten niet noodzakelijkerwijs hun kennis hoeven te delen met anderen. Hiervoor zijn andere affordances nodig. Een hoog risico creëert affordances om robuuste, translokale kennis te produceren, maar hoe de affordance uitwerkt is mede afhankelijk van actorstrategieën omdat er ook andere strategieën mogelijk zijn om risico's te verkleinen dan via productie van translokale kennis. De affordance die wordt gecreëerd door eisen geformuleerd op een hoger niveau in de technische hiërarchie met betrekking tot de gestandaardiseerde performance van technologieën op een lager niveau bleek ingewikkelder te zijn dan in de conceptualisering werd gespecificeerd. Artefacten als de videorecorder bleken in een dubbele dynamiek te zitten waarbij affordances werkten op de componenten (bijv. videokoppen, tape) terwijl er ook effecten waren vanuit het overkoepelende televisiesysteem op de videorecorder zelf. Als de technologie aspecten heeft van een megamachine (zoals in het geval van ATC), kan er een speciaal soort systematische kennis over ontwerpen, implementeren en uitbreiden van architecturale systemen ontstaan. Circulatie wordt mogelijk als deze kennis wordt getransformeerd in een meer abstracte vorm dan concrete vaardigheden op gebied van systeemintegratie en management.

De technologische component van de affordance structuur is per geval verschillend samengesteld, is niet statisch, en kan in verschillende richtingen werken. De totale affordance structuur is afhankelijk van de combinatie met affordances die gegenereerd worden door de actorconstellatie en seculiere ontwikkelingen. De vraag naar welke actoren dominant/veeleisend zijn en welke intermediaire actoren actief zijn is deels empirisch maar ook structureel omdat in verschillende innovatiepatronen verschillende typen actoren dominant/-veeleisend zullen zijn en verschillende typen intermediairen een rol kunnen spelen in de productie van kennis als collectief goed. In het geval van een *user-driven* innovatiepatroon (zoals in de gewapend-betoncasestudie) zullen professionele klanten een belangrijke affordance kunnen creëren. In het geval van een *supplier-dependent* patroon (zoals in de verfcase) zullen producenten zich afhankelijk opstellen van hun toeleveranciers en zullen ze niet zelf het voortouw nemen in het kosmopoliet maken van formuleringskennis. In het geval van een *R&D-dependent* patroon (zoals in de case van videorecording) zijn producenten zelf belangrijke kennisproducenten. In een *mission-oriented* innovatiepatroon (zoals in de casestudie van ATC) zullen missie-actoren een belangrijke rol spelen in het verloop van kosmopolitanisering. Verschillende innovatiepatronen beïnvloeden het tempo, de manier waarop drempels werden overwonnen, en hoe lokaal-kosmopoliete arbeidsverdelingen ontwikkelden.

Het is moeilijk om systematische conclusies te trekken over seculiere veranderingen. Seculiere veranderingen beïnvloeden kosmopolitanisering op een directe manier en op een indirecte manier via technologische affordances (bijv. de opkomst van grote technische systemen in de 20e eeuw) en actorconstellatie affordances (bijv. de opkomst van ingenieursverenigingen en door de overheid gesubsidieerde onderzoeksinstellingen). Wat duidelijk is, is dat uitkomsten van voorafgaande kosmopolitanisering effecten zullen hebben op daaropvolgende kosmopolitanisering. Een van de veranderingen is dat actoren steeds reflexiever worden en in hun handelen rekening gaan houden met het ontstaan van een kosmopoliet niveau. In algemene zin is kosmopolitanisering in de laatmoderne samenleving verschillend van kosmopolitanisering in daaraan voorafgaande periodes. Tegelijkertijd blijft de kwestie van het investeren in translokale kennis waarvan anderen kunnen meeprofiteren bestaan. Kosmopolitanisering zal afhankelijk blijven van affordances zoals die bijv. gegenereerd worden door de aanwezigheid van intermediaire actoren. Het gefaseerde patroon met transities daartussen zal blijven bestaan Met andere woorden, de bevindingen zijn generaliseerbaar. Weliswaar zijn de geselecteerde casestudies voorbeelden van industriële technologieën, maar een eerste check toont aan dat de vier fasen ook herkenbaar zijn in medische en landbouwtechnologieën.

Er kunnen dus ook implicaties nagegaan worden, bijvoorbeeld voor kennismanagement en technologiebeleid worden besproken. De focus op codificering in kennismanagement zou moeten worden verbreed met aandacht voor hoe kennis translokaal gemaakt kan worden. In kennismanagement zou bovendien rekening gehouden moeten worden met het ontstaan van lokaal-kosmopoliete arbeidsverdelingen en hoe organisaties zich hiertoe dienen te verhouden. Ook in technologiebeleid zal bij het stimuleren van kennisdelen (bijv. tussen universiteiten en bedrijven) rekening moeten worden gehouden met de fase waarin kosmopolitanisering zich bevindt. Modulering van de affordance structuur is een van de beleidsopties.

Tenslotte kan worden geconcludeerd dat lokale kennis altijd belangrijk zal blijven in kosmopoliete technologische regimes. Technologieën moeten uiteindelijk werken op hun eigen specifieke locatie. Productieve technologische regimes zijn dus afhankelijk van constructieve combinaties van *'local'* en *'global'*. Met andere woorden, kosmopolitanisering van technologie – de titel van deze dissertatie – leidt tot *"glocal"* technologie.