University of Twente
School of Management and Governance
Chair of Technology Management

Technische Universität Berlin
(Berlin Institute of Technology)
School of Economics and Management

Master Thesis

Platform planning and design for rail rolling stock:

An exploratory study of platform development within Bombardier Transportation

- Non Confidential Version -

Submitted by

Marco Forlingieri

UTwente student number: S 1486969
TUBerlin student number: S 0346521

Internship organisation: Bombardier Transportation, Berlin

Contact e-mail: marco.forlingieri@gmail.com

Supervised by

University of Twente (1st): Prof. Dr. Holger Schiele

University of Twente (2nd): Dr. Erwin Hofman

Technische Universität Berlin: Viktoriia Potishuk

Bombardier Transportation: Dirk Iben

Berlin/Enschede 11.11.2014

Table of Contents

Index of figures

Index of tables

List of Abbreviations

BT	Bombardier Transportation
CAF	Construcciones y Auxiliar de Ferrocarriles
CI	Coupling Index
CNR	China CNR Corporation Limited
COO	Chief Operative Officer
CoPS	Complex Products and Systems
CPI	Change Propagation Index
CSR	China South Locomotive & Rolling Stock Corporation Limited
CTO	Chief Technology Office
DB	Deutsche Bahn
DSM	Design Structure Matrix
EBIT	Earning Before Interest and Tax
ERTMS	European Rail Traffic Management System
EU	European Union
GSC	Global Supply Chain
GVI	Generational Variety Index
HLA	Hierarchic Layer Analysis
HVAC	Heating Ventilation and Air Conditioning
JDDP	Joint Design and Development Process
MFD	Modular Function Deployment
MSG	Market Segmentation Grid
QFD	Quality Function Deployment
RBT	Resource-Based Theory
R&D	Research & Development
SNCF	Société Nationale des Chemins de fer Français
TCMS	Train Control Monitoring System
TCUA	Team Centre Unified Architecture

1. Combining theory and practice in a platform planning and design methodology for rolling stock

1.1. Problem statement and research gap: platform development in complex product environments

As one of the biggest global rolling stock manufacturers, Bombardier Transportation owns a broad project portfolio with different customers all over the world. In recent years, however, the summed complexity of the projects made the company face huge time delays and cost overrun in the development and delivery of products. A cumulated delay of several months and the increasing engineering hours overspend in the development of main projects made BT brings its customer-oriented product development into question. Hence, to keep a competitive advantage in the worldwide rolling stock market, the company decided to migrate towards a platform-based product development.

Multinational engineering-based companies such as BT seek constantly to optimise and integrate their value chain on a worldwide basis by promoting the reuse of shared products, processes and methods. However, due to the many mergers and acquisitions and to the large amount of product development projects their product portfolio is often very heterogeneous and therefore needs to be consolidated and harmonised. The prevailing strategy to achieve product portfolio harmonisation and reuse is the development of product platforms and product families aimed at exploiting product commonality. This consists of reusing standardised components across a large range of products in order to provide product variety while managing complexity and keeping cost low.

In some cases, platforms and product families have been already developed at BT within and outside customer-projects, however concepts, processes, methods and capabilities were often differently understood and applied. Although platform development is not new to the company, explicit structures and processes are not yet in place. In the prior projects, the platform-based product development was often pushed by multiple requests of the same customer or realised “by accident” without a proper platform strategy and planning activity. Experience made during these developments highlighted the lack of guidance available in developing platforms. Notwithstanding the development of previous platforms, BT still lacks consensus on a clear definition of the platform management concepts and the relative planning and design characteristics. This is the main challenge faced by the company:

> A common approach for planning and designing platforms is missing because of the difficulty to deal with different market requirements, standards and regulations, market prices and education of the work force. Due to the varying local processes and lifecycle

requirements, technical specifications of the platform are difficult to anticipate already during the concept design phase. This may lead to a lot of redesign efforts and adaptations. Furthermore, the diversity of engineering capabilities caused by long process of mergers and acquisitions may generate often large and unplanned product variety.

This thesis revolves around this main challenge and seeks to identify platform planning and design characteristics of rolling stock and to develop a systematic planning and design methodology by analysing the specific case of platform development at BT.

1.2. Research goal, central question and research framework: how to plan and design rolling stock platforms

According to Gunzenhauser[1], the most existing research including Meyer and Lehnerd[2], Robertson and Ulrich[3], Moreno Muffato[4], Simpson et al.[5] is not targeted at the operational management level of product executor and mainly addresses the problem from the perspective of consumer goods or the automotive industry. Prior literature does investigate some of the issues described above but usually these are covered in isolation and not in a systematic manner.

Hence, the literature that applies platform concepts and development methods to capital-intensive products and complex systems is still scarce and fragmented. Gunzenhauser's work on "Platform concepts for the systems business"[6] represents a rare exception of platform-based literature targeted at complex products and capital-intensive goods. However, the holistic method introduced by Gunzenhauser results sometimes too complex or not extensive enough for platform planning and design of rolling stock.

To meet the interests of both research and BT, this thesis aims at identifying platform planning and design characteristics of rolling stock and at developing a systematic planning and design methodology for rolling stock platforms. Therefore the main research question is:

RQ: How rail rolling stock providers can develop modular platforms following a systematic planning and design methodology?

The main research question can be divided into four sub-questions, which help to structure the research work:

SQ1: What is the background information needed to plan and develop rail rolling stock platforms?

[1] See Gunzenhauser, 2007, p. 4
[2] For the following description see Meyer & Lehnerd, 1997
[3] For the following description see Robertson & Ulrich, 1998
[4] For the following description see Moreno & Muffatto, 1999
[5] For the following description see Simpson et al., 2006
[6] For the following description see Gunzenhauser, 2007

SQ2: What are the platform planning and design methods available in the literature?

SQ3: What are the planning and design methods available at BT?

SQ4: How can be both platform planning and design methods available in the literature and planning and design methods available at BT integrated and combined in a systematic approach?

To address the exploratory questions, a research framework that is based on both theory-based business problem-solving and case study is deployed. The research design is grounded on a case study research.[7] A detailed description can be found in the fourth chapter. The research framework follows the six-step methodology developed by van Aken and colleagues[8], and its description helps understanding the structure of this thesis (see Table 1).

Research steps	Chapter
1. Conduct literature review and develop preliminary methodology	2
2. Empirical analysis of the business problem	3,4, 5
3. Identify characteristics and consequences of the problem	5.3
4. Explore solution direction and develop intermediate methodology	6
5. Evaluate and validate the methodology	6
6. Derive recommendations to implement the methodology	7

Table 1: Research steps (based on van Aken et al., 2007, p. 54)

With the support of the literature, in the second chapter a preliminary theoretical methodology for platform planning and design for CoPS is conceived (*step 1*. The literature describes the concepts of platform development and modularity, focusing on the research field of CoPS In fact, it is important to point out that the platform planning and design characteristics and the correspondent methods are still kept general in this phase of the study. That means that are not tailored neither to the case of rolling stock nor the case of BT. Since platform planning and design characteristics can be analysed exclusively within platform-based projects, the research is designed as a comparative case study that allows the author to identify similarities and differences across platform-based product developments (*step 2*). The exploratory nature of the study led the author to opt for qualitative empirical evidence to facilitate an in-depth analysis of the phenomenon. Thus, data collection is based on semi-structured interviews, corporate documents and author's observations. In the third chapter a description of the business context in which BT operates is

[7] See Yin, 2009, p. 45
[8] See van Aken et al., 2007, p. 33

provided, focusing on BT's need for a platform-based product development. While the fourth chapter presents the research methodology in details, the fifth chapter provides the empirical evidence of this research by distinguishing between within-case and cross-case analysis. At this phase, the platform planning characteristics identified in the case study and their translation into methodological tasks form *step 3* of the research plan. Based on platform planning and design characteristics for rolling stock an intermediate methodological process is developed in *step 4*. The methodology is then analysed and validated by expert engineers through its practical application (*step 5*). Finally from the presentation of the planning and design methodology recommendations are derived on how BT can easily adopt the planning and design methodology to develop rolling stock platforms (*step 6*).

2. Platform planning and design in CoPS form the theoretical foundations

2.1. Platform development in organisations – key concepts and process considerations

2.1.1. The evolving concept of product platform – definitions and distinctions

The term "product platform" or simply "platform" has already entered the lexicon of most R&D engineers and product managers within different business and industries. The broad use and application of the concept in different business environments generated a variety of definitions and different understandings. Fairly universal, platform thinking is the process of identifying and exploiting commonalities among product offering and target markets to create and deliver new offerings.[9] Platform thinking enables companies to organise and develop a product platform defined by Meyer and Lehnerd as "a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced".[10] Similarly, Muffatto defines a platform as "a relatively large set of product components that are physically connected as a stable subassembly and are common to different final models".[11] In accordance to this understanding, the scope of a product platform is to achieve a certain degree of commonality across different products deriving from a platform solution. The purpose of commonality strategies in product development consists of the reuse and sharing of assets such as components, technologies, interfaces, and/or infrastructures, across product families and derivative products[12]. So far different terms such as product platform, product families and derivative products have been introduced to define a product platform. It is important to clarify that these terms are hierarchically different and cannot be used deliberatively as synonyms. Although the previous definitions provide a clear idea of what a product platform is, they exclusively focus on physical elements without including nonphysical assets. By contrast, alternative streams of research comprise also nonphysical assets. For instance, Ulrich and Eppinger define a product platform as "a set of assets shared across a set of products" by dividing platforms into the following four categories of assets:[13]

- Components: physical parts of the product platform
- Processes: equipment and methodologies used to design and manufacture components
- Knowledge: design, know-how and technology applications
- People and relationships: cross-functional platform development teams, supplier networks, networks of expertise.

[9] See Hofer & Halman, 2005, p. 238
[10] Meyer & Lehnerd, 1997, p. 7
[11] Muffatto, 1999, p. 146
[12] See Boas, 2008, p. 12
[13] Ulrich & Eppinger, 2012, p. 60

The combination of both physical and nonphysical assets "creates a continuum on which physical elements, such as components and systems, provide one pole and the structure, including architectures and interfaces, another". [14] This definition helps to understand the difference between a mere standardisation and a platform solution. Although both use commonality strategies, the standardisation of physical elements across a set of products leads only to the sharing of a modest set of components, whereas a platform solution implies the sharing of a significant portion of development and production assets as well as physical and nonphysical parts. [15]

The terminology used to introduce and define product platform revolves around three basic terms: platform, product families and derivative products. In the literature these terms are often interchanged and used in a conflicting manner to express dissimilar concepts. It is important to shed light on that and clarify that these terms are hierarchically different and cannot be used deliberatively as synonyms. "A product family is the collection of products that share the same assets", whereas a derivative product is a product that belongs to a product family. [16] "A platform is therefore neither the same as a derivative product nor is the same as a product family; it is the common basis of all individual products within a product family". [17]

2.1.2. From product platform and product family to the derivative product

According to the previous definitions, a platform is always linked to a product family and can serve multiple product lines in the market. The leading principle behind the platform concept is to balance commonality (technical needs) and differentiation needs (market needs) within a product family. A basic requirement is therefore the decoupling of elements to achieve the separation of common elements from differentiating elements.[18]

Hence, a platform is only the first outcome of new product development based on platforms and product families. Simpson and colleagues propose a general framework for product development based on platform and product family[19].

The process includes three main phases (see Figure 1):

1) Product platform development
2) Product family development
3) Derivative product development

[14] See Sköld & Karlsson, 2013, p. 64
[15] See Ulrich & Eppinger, 1995, pp. 21-22
[16] See Hofer & Halman, 2005, p. 238
[17] See Hofer & Halman, 2005, p. 238
[18] See Simpson et al., 2006, pp. 4-5
[19] See Halman et al., 2006, p. 30

The process starts with the definition of those physical and nonphysical elements that will form the core part of the platform. These are not only elements of the product architecture (components and interfaces) but also intangible assets, including processes along the whole value chain – i.e. engineering, assembling and manufacturing- and supply chain- i.e. collaboration with global and local suppliers).

The objective of platform development is to optimise the external (market) variety by at the same time minimising the internal (technical) variety.[20]

The effort involves two difficult tasks. First, the platform team should address the question of which market segments to enter, what customer in each segment wants, what product attributes will appeal to those customers. Second, the engineering specialists of the platform team should define which product structure should be adopted to optmise extrenal and internal variety.[21]

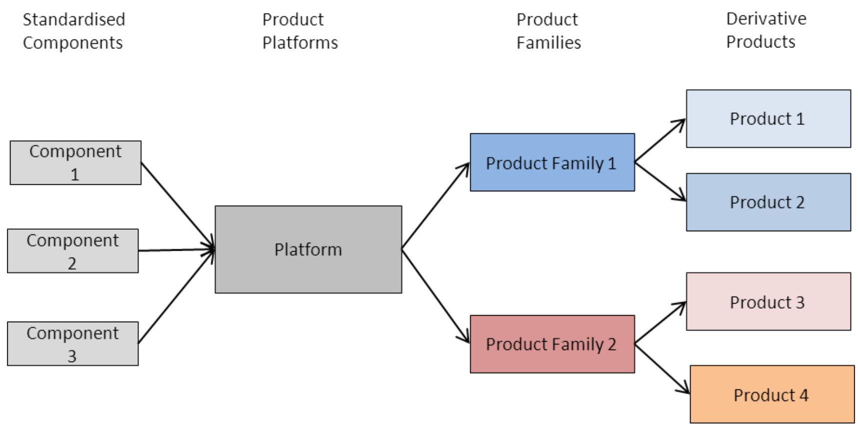


Figure 1: Platform-based product development (based on Halman et al., p. 39)

The second phase consists of designing and developing a product family based on available platform solutions[22]. A product family lays the technical and market basis for the derivative products. According to Halman and colleagues, the more consistent the platform concept is defined and implemented in terms of parts, components, processes, customer segmentation etc., the more effective a company can customise products to the needs of different market segments or customers.[23]

During the third phase, the derivative product is developed. It is based on the product family conceived in the second phase and on further adaptations aimed at meeting the specific market or customer requirements.[24]

[20] See Bongulielmi, 2002
[21] See Robertson and Ulrich, 1998, p. 21
[22] See Halman et al., 2006, pp. 29-31
[23] See Halman et al., 2006, pp. 29-31
[24] See Halman et al., 2006, pp. 29-31

The objective of developing derivative products does therefore not consist of setting up a new basic product structure, but maintaining the product family and adding application parts to customise the product.[25]

The focus of this research is limited to the first stage of the platform-based product development. Although a product platform determines the products that a company introduces into the market during the next five to ten years or beyond, platform planning and platform design are not a one-time effort. New platform development must be pursued on a regular basis, embracing technological changes as they occur and making each new generation of a product family more exciting and value-rich than its predecessors.[26]

2.1.3. Top-down platform strategies: aligning platform strategies with corporate vision and strategy

Porter argues that a corporate strategy enables companies to achieve a competitive advantage.[27] According to McGrath, platform thinking is an important strategy in product development, in particular for those companies that operate in a high technology industry.[28] Such companies are always oriented to penetrate new markets with new products and adapt their products to rapid changes in the marketplace.[29] McGrath defines a product strategy which includes four hierarchical levels: vision, product platform strategy, product line strategy and individual product strategy.[30]

The product vision has the purpose to give a clear picture of what the company is aiming at and to generate common understanding of future products. The vision steers the product platform strategy and provides top-down guidance for the entire product development.[31] At lower level the product platform strategy gives the technological foundations of company's products and the core competences needed to develop product platforms. This includes also decision making about what, when and how product platforms should be developed. The product line strategy is based on the product platform strategy and further specifies the individual products that are built on the product line. Thus, the main objective of a product line strategy is to define the individual products that will serve the selected market segments.[32]

Meyer and Lehnerd define product platform strategies in terms of decision about how products are developed. This includes market segmentation, identification of emerging and growing

[25] See Avak, 2007, p. 33
[26] Halman & Hofer, 2006, p. 32
[27] See Porter, 1986
[28] See McGrath, 1995, p. 13.
[29] See Ratämaki, 2004, p. 44
[30] See McGrath, 1995, p. 13
[31] See Ratämaki, 2004, p. 44
[32] See Ratämaki, 2004, p. 45

markets, benchmarking of competitive products, but overall, the definition of the current and the future product portfolio based on the platform.[33]

Thus, the key element of platform strategy is the ability to foresee the possible customer needs years ahead and according to the most plausible future scenario make technological choices that will support the product platform strategy for years.[34]

2.1.4. The industrial application of platforms: benefits and rationales for implementing commonality strategies

Cost and time efficiencies, technological leverage and market power can be achieved when companies redirect their thinking and resources from single products to product families based on robust platforms.[35] Most of the benefits of platform development have been universally shared by different industrial contexts.

The Volkswagen A and C platforms[36] and the platform-based motor truck family of Volvo[37] in the automotive industry, the product families Boeing 777 and the Airbus A380[38] in the aerospace industry as well as the more recent global platforms of Schindler[39] in the elevator industry are only a few examples of platform thinking applied in different business environments.

Much has been written on the topic of platform and commonality, primarily stemming from seminal work by Utterback and Meyer[40] and Robertson and Ulrich[41] although earlier work can be found from 20 years previous.[42] Although these early works cited a number of general benefits, there is no consensus on the list of universal benefits of platform strategies.[43]

Cameron and Crawley recently attempted to combine the benefits of platform strategies by clustering them into three categories: cost savings, risk benefits and revenue benefits.[44] Platform strategies contribute to the reduction of resources (cost and time) in all stages of the product development. In fact technology transfer and asset reuse across different projects may result in “a significant reduction of lead time and engineering hours for each new product compared to a completely new design”.[45]

By using standardized and pre-tested components, the accumulated learning and experience in general may result in higher product performance and lower product risk.[46] Platform thinking

---

[33] See Meyer & Lehnerd, 1997, pp. 52-53
[34] See Ratämaki, 2004, p. 45
[35] See Halman & Hofer, 2006, p. 32
[36] See Boas, 2008, p. 14
[37] See Zha & Srira, 2006, p. 524
[38] See Boas, 2008, p. 13
[39] See Gunzenhauser, 2007
[40] See Utterback and Meyer, 1993
[41] See Robertson and Ulrich, 1998
[42] See Collier, 1981
[43] See Cameron & Crawley, 2014, p. 5
[44] See Cameron & Crawley, 2014, p. 6
[45] Magnusson & Pasche, 2014, p. 437
[46] See Halman & Hofer, 2006, p. 31

enables companies to better manage the increasing need for high product variety and product customisation by containing the overall level of complexity. By decreasing and simplifying the total number of parts and processes companies can reduce systemic complexity of a given product portfolio.[47] The setup of a robust product platform solution enables companies to gain market domination and grants them access to new markets.[48] Platform solutions are a strategic tool that can help companies to achieve technological competitive advantage and to leverage common assets across products or projects "serving as top-down planning approach to maximise market leverage from common technology".[49]

2.2. Modularity of platforms: product architecture, modules and interface specifications as key concepts

2.2.1. The modular architecture: embedding modularity in product architecture

The reuse and sharing of the physical and nonphysical assets across different products is only one of the characteristics of a platform. Every platform embeds "an architecture that enables other features to be added or existing features to be removed in tailoring derivative products to special market niches".[50]

Therefore, the relationship between platforms and architectures is crucial to understand the nature of platforms and hence the reuse and exchange of assets across platform-based products. In general terms, Ulrich and Eppinger define product architecture as "the scheme by which the function of the product is allocated to physical components".[51] In other words, the breakdown of the product design into functional components and the definition of the related interfaces, that define the functional relationship between those components, constitute the architecture of a product.[52] The product architecture defines the design rules of the product and guides the subsequent design process.[53]

Before introducing the concept of modularity, it is necessary to distinguish between two typologies of product architecture: modular architecture and integral architecture. The main difference lays in the component configuration and in the functional allocation. In fact, a pure modular architecture includes a "one-to-one mapping from functional elements into the physical components of the product and specified decoupled interfaces between components".[54]

[47] See Magnusson & Pasche, 2014, p. 437
[48] See Meyer & Lehnerd, 1997, p. 53
[49] Meyer & Lehnerd, 1997, p. 53
[50] Baldwin & Woodard, 2008, p. 6
[51] Ulrich &Eppinger, 2012, p. 41
[52] Liu & Chen, 2005, p. 772
[53] See Ulrich & Eppinger, 2012, p. 41
[54] Ulrich, 1993 p. 422

By contrast, an integral architecture “includes complex mapping between functional elements and physical components as well as coupled interfaces between components”.[55]

Therefore, modular product architectures are characterized by a high degree of independence between components (modules) and their interfaces. Consequently, products and systems show a high degree of modularity when their architecture permits components to be disaggregated and recombined into new configurations with little loss of functionality.[56] Contrary to modular products, those products that have tightly coupled interfaces and do not allow components separation without the loss of functionality are characterised by having an integral architecture (see Figure 2).[57]

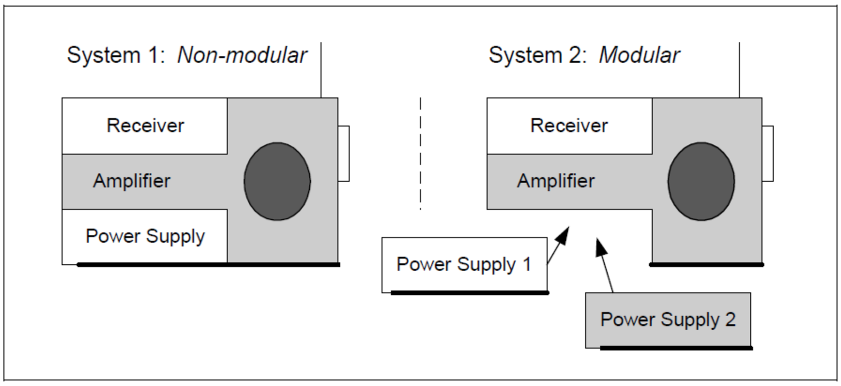


Figure 2: A comparison between an integral and a modular radio (Miller & Elgard, 1998, p. 11)

Schilling defines modularity as “a continuum describing the degree to which system’s components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the design rules of the product architecture enable (or prohibit) the mixing and the matching of components”.[58] Components that embed a modular architecture are defined as modules. Modules are thus sets of components that are highly coupled and perform one or more functions.[59] They have strong internal coupling and loose external coupling with other modules. Modules are also defined “as an independent building block of a larger system with a specific function and well-defined interfaces.[60] The first attribute focuses on the functional aspect, whereas the second refers to the high degree of independence between components ensured by predefined and standardised interfaces.[61] The combination of both attributes allows changes on few isolated functional elements of the systems without necessarily affecting the design and the functionality of other modules.[62] By contrast, in a highly coupled

[55] Ulrich, 1993 p. 422
[56] Schilling, 2000, p. 312
[57] Schilling, 2000, p. 316
[58] Schilling, 2000, p. 312
[59] See Miller & Elgard, 1998, p. 4
[60] Höltta, 2005, p. 27
[61] See Tamaskar et al. 2014, p. 128
[62] See Schilling, 2000, p. 316

system a small change on a few functional elements may lead to a complete or partial redesign of the system. [63]

Modules can be classified in basic modules, auxiliary modules, special modules and adaptive modules. Respectively these modules provide basic functions, auxiliary functions, special functions and adaptive functions. By contrast, those components that fulfil customer-specific not predictable functions are classified as non-modules (see Figure 3).[64]

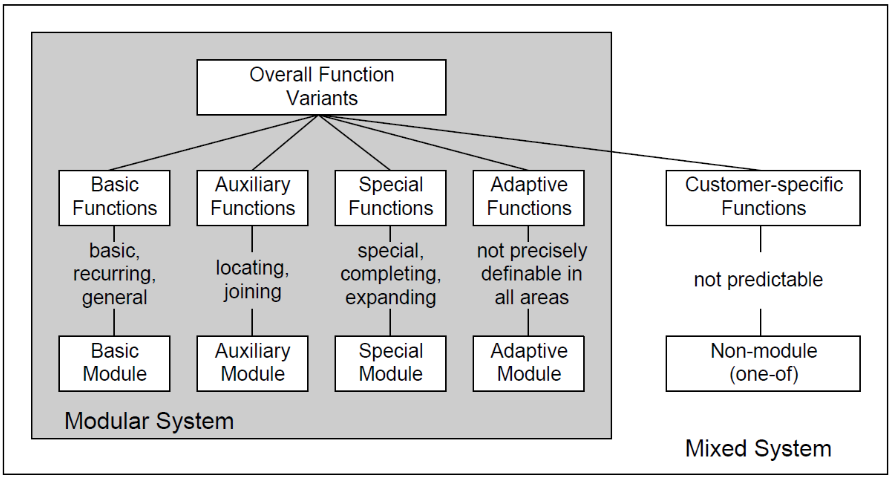


Figure 3: Function types and module types in modular and mixed product systems (Miller and Egard, 1998, p. 5)

The combination of such modules within a platform generates an adaptive platform that combines different types of functions in a constrained balance: (1) basic functions or core functions of static nature that exist in all derivatives, and (2) the remaining functions or innovation functions which are adaptive and change their technical solutions frequently[65]. Those adaptive platforms use the logic of constraint-based product development to define best-suited design for product functions. According to ElMaraghy adaptive product platforms lend themselves to dynamic and evolving product families.[66]

2.2.2. Standardisation of interface specifications as key enabler to develop modular platforms

Modules constitute the physical or conceptual grouping of modular platform architectures and their degree of coupling and recombination is defined by the interface specification.[67] According to Ulrich an interface specification defines the “protocol for the primary interactions across the

[63] See Schilling, 2000, p. 316
[64] See Miller and Elgärd, 1998, p. 5
[65] See ElMaraghy, 2009, p. 30
[66] See ElMaraghy, 2009, p. 30
[67] See Ulrich, 1993, p. 423

component interfaces, and the mating geometry in cases where there is a geometric connection".[68] Hence, interfaces can be both physical and nonphysical depending on the type of interaction protocol. They contribute to both commonality and compatibility in products that derive from the same platform. Moreover, in platform architecture the specification of the requirements for components interfaces enables components to become decoupled.[69] The key enabler of managing interfaces within a modular platform is the standardisation of the interface protocol within the related module-to-module interaction. This is a crucial action to facilitate modules substitution and recombination. [70]

To standardise the interactions between the modules of a platform, platform architects must specify and define different types of interfaces:[71]

- Spatial and attachment interfaces that define how the modules attach to each other and how the spatial volume is allocated to components
- Transfer interfaces that provide electrical and information input/outputs
- Control and communication interfaces that monitor the state of the components or eventual changes in the system
- User interfaces that define how components receive information from the user
- Environmental interfaces that enable system's modules or components to interact with the external environment

Such interfaces provide the properties for components to interact and correlate. They possess interacting functions such as connecting, transferring, transforming, and controlling.[72]

In other words, the particular interfaces of components construct informative structures that define the necessary input and output of the design process.[73]

Companies that aim to develop modular platforms have to consider both internal and external interfaces when they evaluate their interface strategy. [74] Internal interfaces coordinate functional elements to perform full product functions, whereas external interfaces connect external products- i.e. complementary products) and users, and affect the upper level performance of the system. [75]

The basic enabler of any interface strategy aiming at platform development is the standardisation of interfaces. It means that component interfaces, once fully specified and standardized, must not be changed during subsequent component development processes.[76]

---

[68] Ulrich, 1993, p. 422
[69] See Liu & Chen, 2005, p. 774
[70] See Ulrich, 1993, p. 424
[71] See Sanchez, 2000, p. 10
[72] See Liu & Chen, 2005, p. 774
[73] See Liu & Chen, 2005, p. 774
[74] See Liu & Chen, 2005, p. 775
[75] See Liu & Chen, 2005, p. 775
[76] See Sanchez, 2000, p. 16

Standardized component interfaces provide the essential information structure that serves, in effect, as means to coordinate concurrent engineering in platform development.[77]

Changing interface specifications midstream in a concurrent development process can disrupt the design work of module development groups, lead to redesigns of components and result in additional development cost and longer time-to-market.[78]

For instance, in Chrysler's vehicle development processes or in Philips' modular development process, once interfaces between subsystems are defined, they become "hard points" or "holy parts" that are not allowed to change during the development project. [79]

After the interface specifications for a new architecture are being worked out, the platform development team should be prepared to work with the same interfaces throughout the design and development process. [80]

Standardised interface parameters and protocols within the boundaries of a modular architecture define the design rules of the platform. Such as "design rules make the adaptation of the modular platform architecture to different product families possible".[81] This occurs because both design rules and standardised interfaces set which components should remain stable and which should vary across products families and derivative products. In this context, the platform solution as a whole becomes evolvable. It means being capable to adapt at low cost and risk without losing platform identity and continuity of design.[82] However, in this phase not only is it difficult to ascertain all of the interfaces *a priori*, but it is also difficult to be sure that all of the physical and nonphysical elements themselves have been adequately enumerated and validated under the limits of the design rules.[83]

Standard interface specifications facilitate the splitting of the system in different modules and, in turn, the plurality of valuable design option. At the same time, such a modularization moves decisions from a central point of control to the individual modules but always within the boundaries set by the general design rules. [84]

In summary, a platform architecture owns a special type of modularity, in which a product or system is split into a set of module typologies that provide different functions. Generic modules, that fulfil basic functions and are highly reusable, form the "frozen part" of the platform, whereas the module variations and adaptations form the customised part.[85] The interoperability between modules is made possible by the visible design rules and hidden design parameters of modularity

[77] See Baldwin & Clark, 2004, p. 10
[78] See Sanchez, 2000, p. 16
[79] See Sanchez, 2000, p. 16
[80] See Sanchez, 2000, p. 16
[81] See Yassine & Wissman, 2007, p. 120
[82] See Baldwin & Woodard, 2008, p. 9
[83] See Yassine & Wissman, 2007, p. 120
[84] See Yassine & Wissman, 2007, p. 120
[85] See Baldwin & Woodard, 2008, p. 6

as well as by the standardised interface specifications that allow module substitution within the product architecture.[86]

2.2.3. Changing environmental factors influence company to adopt modular platforms: understanding system migration towards modularity

According to Shilling's definition of modularity of systems, since all systems are characterised by some degree of coupling between components, and very few systems have components that are completely inseparable, almost all systems are, to some degree, modular.[87]

Although modularity seems to be a general characteristic of system, even in systems in which de-coupling and recombination is possible, there might be some parts of the systems that work better when they are tightly coupled. Schilling defines as synergistic specificity the degree to which a system achieves greater functionality by its components being specific to one another.[88] High levels of synergistic specificity make systems adopt integral product architectures. By contrast when systems components achieve little synergistic specificity, the system is very likely to adopt a modular architecture. [89] Modularity is a basic attribute of platforms. Thus, the product development of those systems that show low synergistic specificity and, in turn, high coupling and recombination has great chance to turn into a modular platform development process.

Fairly universal, systems are evolvable entities that follow a continuum, shifting and adapting from one configuration to another according to the evolution of the context in which they operate. [90] System migration from synergistic specificity to modularity always depends on contextual factors that trigger and facilitate the change. Since the synergistic specificity is at the core of many complex systems, it can act as a strong force against system's shifting to modularity.[91]

In "the general modular system theory", Schilling describes the migration of systems towards or away from increasingly modular forms, including the environmental factors and the internal forces that facilitate or contrast the transition.[92]

Shilling identified heterogeneity of inputs, heterogeneity of demands and urgency as external forces in favour of modularity, whereas synergistic specificity and inertia as internal force against modularity (see Figure 4).

[86] See Mikkola, 2006, p. 129
[87] See Schilling, 2000, p. 312
[88] See Schilling, 2000, p. 316
[89] See Schilling, 2000, p. 316
[90] For the following description see Holland, 1999
[91] See Schilling, 2000, p. 316
[92] See Schilling, 2000

According to Schilling´s definition of modularity, the primary action of modularity is to enable heterogeneous inputs to be recombined into a variety of configurations to meet heterogeneous demands. [93]

As consequence, the more heterogeneous the inputs to compose a system, the more possible configurations are attainable through the recombination enabled by modularity.[94]

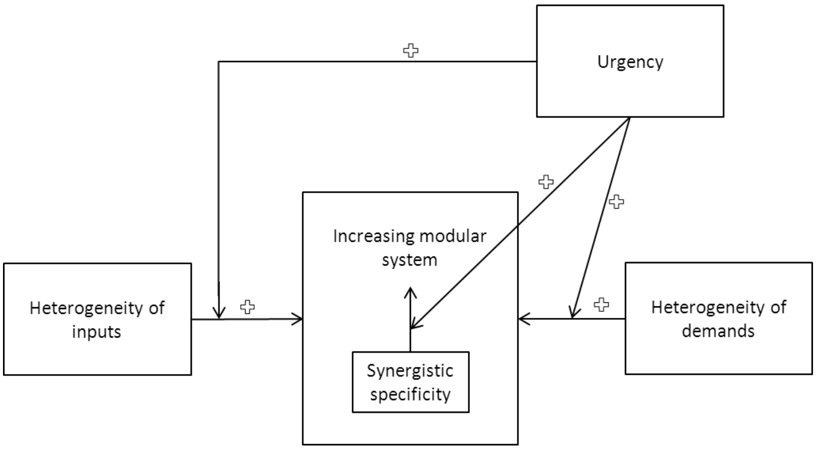


Figure 4: Casual model representing systems migration towards modularity (Schilling, 2000, p. 319)

For instance, systems within business contexts that show heterogeneous demands of corporate capabilities, technical solutions and suppliers, combined with heterogeneous customer demands, have powerful incentives to adopt a modular configuration.

Synergistic specificity and inertia of systems of reacting to contextual changes are factors that contrast the pressure provoked by the external forces.[95] They act as inhibitors and delay system's migration towards modularity. In contrast, another force defined as urgency- i.e. in terms of system's reaction to competitive intensity or time constraints- can catalyse the system's migration to the new form.[96] Urgency may derive from new competitors entering a market with appealing products and faster time-to-delivery or from shorter product lifecycle caused by technological changes.[97]

Companies that operate in an environment where the pressure created by both heterogeneities and urgency overcome the system's inertia and synergistic specificity are likely to develop modular platform solutions to respond to the evolution of the environment and its challenges.

[93] See Schilling, 2000, p. 317
[94] See Schilling, 2000, p. 317
[95] See Schilling, 2000, p. 318, 326
[96] See Schilling, 2000, p. 326
[97] See Schilling, 2000, pp. 326-328

2.3. CoPS: definition, characteristics and potential for modular platforms

2.3.1. The nature of CoPS background and definition

CoPS are a generic category of industrial goods defined as "high-cost, engineering-intensive products, systems, networks and constructs".[98] Different aspects of complexity are included in their definition such as the large numbers of tailored components, the breadth of specific knowledge and skills, the bundle of organisations involved and other critical factors.[99] CoPS are high costly and are formed by many interconnected and customised parts designed to be integrated within a structure.[100]

CoPS are designed and produced on a project basis, according to the requirements of large professional and institutional customers.[101] Contrary to the consumers of mass-produced products, CoPS customers are intimately involved in the design of the product.[102] Such a high degree of customisation leads to the production of low volume of products that are often characterised by high levels of customer involvement, uncertainty of design requirements, complex supply networks, long delivery times and highly regulated design and operational environments.[103] It is worth noting that these characteristics make "design and development activities pivotal in the supply of these goods".[104] Finally, CoPS development is often realised through large projects where multiple stakeholders act under different responsibilities and roles. Hence, CoPS providers are generally systems integrators that work jointly with customers, suppliers, regulators and governmental agencies.[105]

2.3.2. CoPS Network: inter-firm network generates a sustainable competitive advantage

Companies that develop CoPS often operate as system integrators that purchase a large part of their products – i.e. subsystems and complex components - from external sources.[106] Company´s behaviour of relying on external sources is explained through the application of the "relational view of resources-based theory". The theory extends the core tenets of RBT by integrating the perspective of the relational network theory "to explain how inter-firm cooperation can generate sustainable competitive advantage".[107] Relational view of RBT argues that the resources generating competitive advantage can overcome firm boundaries and depend on inter-firm relations. Therefore, "the sources of competitive advantages are not only from the internal

[98] Hobday, 1998, p. 690
[99] Hobday, 1998, p. 690
[100] See Davies and Hobday, 2005, p. 12
[101] See Davies and Hobday, 2005, p. 6
[102] Davies and Hobday, 2005, p. 9
[103] See Gil, 2007, p. 981
[104] Prencipe, 1998, p. 5
[105] Gil, 2007, p. 981
[106] See Hobday, 1998, p. 695
[107] Wong, 2011, p. 35

resources owned by a company but also from the external resources in the relational networks". [108].

Although with differences depending on the form of inter-firm relations, partnering companies can generate relational competitive advantages through important joint actions such as investments in relation-specific assets, substantial knowledge exchange, complementary resources and capabilities; and effective governance. [109]

For instance, the organizational learning literature has confirmed that inter-organisational learning through knowledge sharing between trading or alliance partners is critical to competitive success.[110]

Furthermore, a relevant group of contributions started focusing on suppliers' involvement, emphasizing both the critical role played by suppliers in the achievement of high performances in new product development and how the creation of tight relationships with suppliers is based on strong interactivity, continual information exchange and the deep reciprocal reliance.[111] This new focus is centred on managing suppliers as sources of knowledge and know-how rather than simple vendors of parts or as sub-contractors. [112]

2.3.3. CoPS Characteristics: integral product architectures complicate collaboration in product development and limit knowledge and component transfer across projects

Following Simon's description of complex systems[113] CoPS architecture is defined by "multiple levels of hierarchy".[114] In line with their hierarchical structure, CoPS are characterised by three basic elements: product architecture, subsystems and mechanisms of control that are often software-based.[115] Each subsystem provides multiple specific functions and is synergistically integrated to the system to achieve a common goal. [116] To meet the high performance requirements of customers, CoPS tend to have integral architectures formed by many customised components linked via complex interfaces.[117] The large number of tailored components not only complicates component integration but also the coordination of different actors in the product development activities.[118] Since CoPS integrators often operate worldwide across a multi-project

---

[108] Wong, 2011, p. 35
[109] See Chen et al. 2013, p. 393
[110] See Chen et al. 2013, p. 393
[111] See Corso et al., 2001, p. 348
[112] See Corso et al., 2001, p. 348
[113] For the following description see Simon, 1995, p. 26
[114] Hobday, 1998, p. 692
[115] See Hobday, 2000, p. 873
[116] See Hobday, 1998, p. 694
[117] See Gil, 2007, p. 981
[118] See Hobday, 1998, p. 695

portfolio of complex products, the quantity of possible alternative system architectures throughout the large portfolio of projects may cause in additional coordination problems.[119]

Collaboration in CoPS development is essential because the variety of skills and engineering inputs expand far beyond the capabilities of the system integrator. The high degree of specialisation in CoPS dictates integrator companies to work together with specialist suppliers.[120]

Therefore, system integrators are companies that purchase a large part of their products from external sources. They take responsibility for the design and assembly but they outsource most of the production to suppliers. In case of supplier involvement in product development the supplier carries out also some functional specifications and engineering responsibilities.[121] The role of supplier in product development mainly depends on “the proprietary sensitivity of the component and on the degree of supplier involvement in design and manufacturing”.[122] Although, different possible supplier-integrator collaborations exist, the role of supplier remains of primary importance in CoPS development.

According to ElMaraghy and colleagues, the nature and degree of customer involvement differentiate between mass customisation, extreme customisation and true customisation.[123] All three variants differ from mass-consumer production where the customer has not direct influence on the final configuration of the product. CoPS imply high personalisation of products that means “active and closer involvement by customers in defining some or all product features and, hence, results in unique products”.[124] CoPS are mostly business-to-business, capital goods tailored to the needs of specific customers that operate in particular environmental or market conditions.[125] Such a close relationship allows customers “to feed their needs directly into the specification, design, development and manufacture of CoPS”.[126] High customisation makes process learning and reuse of solutions between CoPS and between CoPS generations mostly limited to “accidental” reuse.[127] This depends on the difficulties experienced by CoPS producers to transfer knowledge and parts from a project to another, varying customer needs and specification of the components inputs.[128]

Furthermore, CoPS industries are regulated by standards and norms that differ widely across countries because of the high degree of discretion and autonomy in regulatory processes.[129] Different intensive regulatory standards together with customer preferences drive CoPS

[119] See Gil, 2007, p. 981
[120] See Hobday, 1998, p. 695
[121] See Hsuan, 1999, p. 202
[122] Hsuan, 1999, p. 202
[123] See ElMaraghy et al., 2013, p. 631
[124] ElMaraghy et al., 2013, p. 632
[125] See Hobday, 1998, p. 705
[126] Hobday, 1998, p. 705
[127] See Hobday, 1998, p. 705
[128] See Hobday, 1998, p. 705
[129] See Hobday, 1998, p. 695

development and limit knowledge and component transfer within the CoPS portfolio of a company. [130]

To conclude, CoPS development projects involve several stakeholders including customers and suppliers. Thus, high collaboration with key suppliers is needed in order to accomplish specific customer requirements. However, both the high degree of customer involvement and the high level of performance influence CoPS to have integral product architectures varying from a project to another. This tendency of CoPS towards having integral product architectures complicates the collaboration between different stakeholders and limits the transfer of knowledge and parts across CoPS projects.

2.3.4. Is there a potential for platforms in CoPS?

Notwithstanding the body of literature concerning the concept of platform and its application in practice, according to Hofer and Halman, there is gap when it comes to the application of the concept to CoPS.[131]

CoPS have been established as a distinct research area for products and systems, where a complete decoupling of components is rarely feasible, and the variety of subsystem combinations can cause high levels of uncertainty and risk in system design, production, and integration.[132]

As described before, the architecture of complex systems is characterized by multiple levels of hierarchy and a wide range of architectural choices. Accordingly, CoPS have a project-specific system design where the high engineering efforts lead to high resource expenditures, time-to-delivery delay and risk.[133]

Based on a literature review of previous researches on platform thinking in complex systems, Halman and Hofer found out that companies often limit commonality and reuse of solutions to a low hierarchical level of the product architecture.[134] However, in a situation where complex systems face the external forces described by Schilling such as heterogeneity of inputs, heterogeneity of demands and urgency, it would be highly beneficial for CoPS shifting from integral system architectures to modular architectures (see 2.2.3).

Halman and Hofer claim that in order to achieve the benefits of commonality and modularity, CoPS should extend platform potential to the system architectural layout and to a higher hierarchical level in the system architecture.[135]

According to Halman and Hofer, “designing a product family based on a layout platform means defining *a priori* (and, therefore, standardizing) the arrangement of subsystems of which the

[130] See Hobday, 1998, p. 695
[131] See Hofer and Halman, 2005, p. 240
[132] See Hofer and Halman, 2005, p. 240
[133] See Hofer and Halman, 2005, p. 240
[134] See Hofer and Halman, 2005, p. 240
[135] See Hofer and Halman, 2005, p. 240

product consists".[136] This standardized configuration is a deliberative restriction of the design choices and serves as a basis for derivative product developments. Hofer and Halman argue that such a deliberative restriction of architectural configurations is the only choice for CoPS to adopt a platform-based product development.[137]

2.4. Platforms for CoPS: identifying appropriate platform development characteristics

2.4.1. Planning for variety: ensuring product variety to meet distinctive customer requirements, market requirements, standards and rules

The increase of product portfolio variety increases complexity and consequently risk in product development.[138] However, variety has a multitude of reasons including different regional requirements, large number of market segments with different needs and standards as well as customer's demand of new product functions and features.[139]

Planning for variety is a design strategy and methodology to help designers satisfy individual customer needs, gain market shares and remain competitive in spite of increased product variety.[140] It provides methods to determine the components "to be redesigned based on the external drivers of generational change including: customer requirements, cost reduction, regulations and standards".[141] Product parts that are highly integrated within the product architecture represent a core to be treated as geometry constraint (ElMaraghy et al., 2013, p. 632). Core modules forming the product platform contain highly coupled components. The standardization of core modules (geometry constraints) represents an important element for controlling the product complexity costs.[142] According to ElMaraghy and colleagues, the main criterion used to define core components, which should be standardized across all product variants, is to reduce the effect of modifications of product attributes.[143]

In platform planning, two types of variety exist: variety within the current product portfolio and variety across future generations of the product.[144] The first is defined as generational variety, whereas the second as spatial variety. Design for variety allows companies to plan the product line such that it isolates the components that are likely to change and differ from the core part of the platform.[145]

---

[136] Hofer and Halman, 2005. P. 240
[137] See Hofer and Halman, 2005, p. 241
[138] See Hobday, 1998, p. 694
[139] See ElMaraghy et al., 2013, p. 629
[140] See ElMaraghy et al., 2013, p. 632
[141] ElMaraghy et al., 2013, p. 632
[142] See ElMaraghy et al., 2013, p. 632
[143] See ElMaraghy et al., 2013, p. 632
[144] See Martin and Ishii, 2002, p. 215
[145] See Martin and Ishii, 2002, p. 214

QFD is a well-known tool for identifying customer requirements and their relationships to product specifications.[146] However, requirements do change with time and with customer's environment.[147] Careful product variants planning based on different market segments and requirements for several years into the future is required. GVI is a method in support of planning and managing variety.[148]

2.4.2. Design for changeability: reusing modular architectures and modules across projects

Fricke and Schulz identified three aspects that are major drivers of the development of complex systems in the future: dynamic marketplace, technological evolution and variety of environments.[149] In order to cope with these challenges, system architectures have to incorporate the ability to be changed easily and rapidly as well as the ability to be robust enough to serve different environments.[150] Design for changeability is a key principle applied to incorporate changeability into system architecture in order to adapt it to predictable and unpredictable changes throughout the lifecycle of the system. Thus, it could also include using an existing architecture for possible derivatives.[151]

Following Steiner´s work[152], Fricke and Schulz suggest that products can benefit from embedding system changeability only if they own certain natural characteristics.[153]

These characteristics are summarised below:

- The architecture is used for different products with a common basic set of attributes
- The system has stable core functionality but variability in secondary functions and/or external styling
- The system has a long lifecycle with fast cycle times of implemented technologies driving major quality attributes- i.e. functionality, performance, reliability, etc.
- The architecture and system are highly interconnected with other systems sharing their operational context
- The system requires high deployment and maintenance costs

[146] For the following description see chapter 2.5.2.2
[147] See ElMaraghy et al., 2013, p. 632
[148] For the following description see chapter 2.5.2.3
[149] See Fricke and Schulz, 2005, p. 343
[150] See Fricke and Schulz, 2004, p. 345
[151] See Fricke and Schulz, 2004, p. 346
[152] For the following description see Steiner, 1999
[153] See Fricke and Schulz, 2004, p. 345

Since CoPS own all of these characteristics, CoPS companies cannot avoid embed changeability in their platforms if they want to achieve adaptability to predictable and unpredictable changes throughout the lifecycle of the system.

Changeability is characterised by four aspects: robustness, flexibility, agility and adaptability. [154] Each aspect contributes to guide engineers in designing the architecture of complex system platforms.

Robustness refers to system's ability to be insensitive towards changing environments. [155] Taguchi argues that robust systems serve their functionality under varying operating conditions without modifications and adaptation to changing environment or market needs.[156]

Flexibility consists of system's ability to be shaped and changed. In this case changes from external are needed to face the changing environment or market needs. [157]

Agility corresponds to system's capability to be changed rapidly. This means that external changes should be implemented to face the changing environment or market needs. [158]

Finally, adaptability refers to system's ability to adapt itself towards changing environments and market needs. As mentioned before adaptable systems fulfil their functionality under varying operating conditions. This means that no changes from external have to be implemented to cope with changing environments. [159]

The four aspects of changeability include some paramount principles that enable complex systems to adopt changeability. These principles distinguish between basic principles that support all four aspects of changeability, and extending principles that support only some aspects of changeability (see Figure 5).[160]

Since the principles have positive and negative correlations, it is therefore necessary to select a balanced set of principles for different aspects and degrees of changeability. The risk is indeed to neutralise the effects of certain principles on the system.[161]

[154] See Fricke and Schulz, 2004, p. 347
[155] See Fricke and Schulz, 2004, p. 347
[156] See Taguchi, 1993, p. 26
[157] See Fricke and Schulz, 2004, p. 347
[158] See Fricke and Schulz, 2004, p. 347
[159] See Fricke and Schulz, 2004, p. 347
[160] See Fricke and Schulz, 2004, p. 348
[161] See Fricke and Schulz, 2004, p. 348

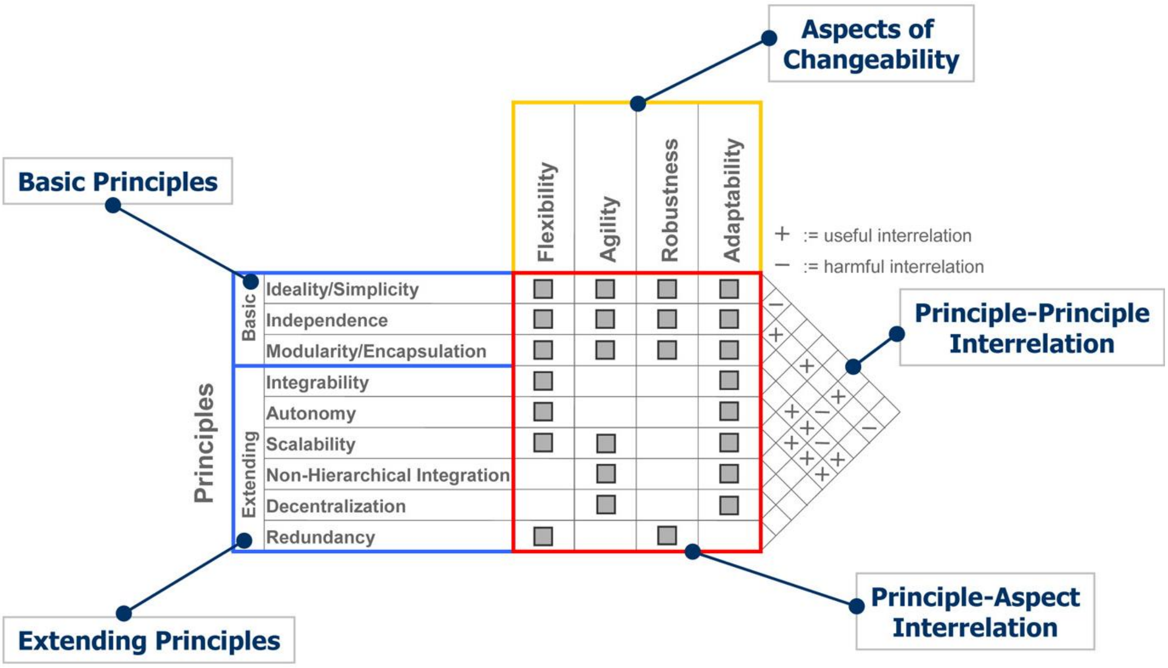


Figure 5: The changeability aspect-principle-correlation matrix (Fricke and Schulz, 2004, p. 348)

The principle of ideality/simplicity affirms that a system should minimise the number of interfaces, minimise the number of secondary functions and reduce and focus on already existing subsystems.[162] Then, the principle of independence has the scope of realising components with design parameters- consisting of the function embedded in the component- that are not affected by changes in other components. [163]

Finally, in accordance with Schilling's definition, modularity is applied to create a system architecture that clusters system's functions into various modules while minimizing the coupling among the modules. [164] According to Fricke and Schulze other supplementary principles should be considered to enable system changeability.[165] These are: integrability, autonomy, scalability, non-hierarchical integration, decentralisation and redundancy. [166]

To enable changeability, Fricke and Schulze claim that an in-depth understanding of the interfaces is needed. DSM and variants of the method such as the CPI are useful tools in support of coupling analysis and design of changeable systems. [167]

---

[162] See Fricke and Schulz, 2004, p. 348
[163] See Fricke and Schulz, 2004, p. 350
[164] See Fricke and Schulz, 2004, p. 350
[165] See Fricke and Schulz, 2004, p. 352
[166] For the following description see Fricke and Schulz, pp. 352-354
[167] For the following description see chapter 2.5.2.4

2.4.3. Design Network: external inputs and design responsibility in platform development through supplier involvement

According to Corso and colleagues, starting from the concurrent engineering concept of the inter-functional team within the company, an important stream emerged in product development literature further expanding the scope of the new product development process: taking into account the importance of assimilating and integrating knowledge from outside the traditional boundaries of in-house product and platform design.[168] As mentioned above in chapter 2.3.2 supplier integration in new product development is an important approach of integrating external resources in design of new products. In particular, a new platform characterised by a modular product architecture "requires a new combination and integration of complementary capabilities that hopefully exist within a set of companies".[169] Although integrated relationships of suppliers and buyers are found to be less efficient in the short run, they do provide more opportunities to achieve a reciprocal competitive advantage in the long run.[170]

Supplier involvement, which is defined as the tasks suppliers carry out on behalf of the customer and the responsibilities they assume for the development of a part, process or service, has been proven to result in many advantages for the process of new product development.[171] The most important are lower development time and product costs, fewer engineering changes, higher quality and product reliability, shorter time to market, detailed process data but overall, for the purpose of this research, modularised components and subsystems configured for reuse.[172] Supplier-buyer collaboration in platform development provides complementary knowledge and complementary resources that both collaborating companies bring to the process. The combination of diverse capabilities enables companies to generate new technologies and create products that would not have been possible using only homogeneous knowledge and resources.[173]

Monczka and colleagues defined a model of supplier level of responsibility to categorise the spectrum of supplier involvement in the design phase from no involvement to complete outsourced design and development.[174]

Following Monczka and colleagues' categorisation, four different degrees of supplier involvement are identified. These are: no involvement, "white box", "grey box" and "black box".[175]

[168] See Corso et al., 2001, p. 347
[169] Hofman et al., 2009, p. 34
[170] Hofman et al., 2009, p. 34
[171] See Van Echtelt et., 2008, p. 182
[172] See Feng et al., 2010; Monczka, 2010; Ragatz et al., 2002;
[173] See Ylimaki, 2014, p. 2
[174] For the following description see Monczka et al., 2000
[175] See Petersen et al., 2005, p. 378

The first approach is self-explaining and treats suppliers only as producers without any inclusion in the design activities. In the second approach, the “white box”, discussions are held with suppliers about design requirements but the buyer is fully responsible for all design and specifications decisions.[176] In the third approach, the “grey box”, the buyer and supplier enter into a formalised joint development effort, which may include information and technology sharing and joint decision.[177] In the last approach, the “black box” the supplier is informed of customer requirements and then is given almost complete responsibility for the purchased part, with only review and concurrence on the specifications by the buying company. This latter form of involvement constitutes the highest level of supplier integration in design and development.[178]
The choice of a supplier involvement approach varies depending on the type of subsystem and component and reflects the value created by the supplier for the buying company.[179]
A supplier provides value for its customers in several ways. In its simplest form, this value is expressed by the market price of the resources that can be transacted through market competition.[180] This dimension of value creation describes the immediate cost-and-revenue effects of a supplier relationship for the buyer, defining values exclusively in monetary terms. However, when the value creation requires sustained joint efforts, the value is alos dependent on the characteristics of the particular supplier–customer relationship such as knowledge absorption, innovation potential and access to new markets.[181]
According to Möller and Törrönen supplier’s value creation potential can be evaluated by the difference between the total benefits received and the total sacrifice incurred.[182] Following on the aforementioned framework to classify different degrees of supplier responsibility, no involvement of supplier incurs when the component is perceived as a standard and has many substitute suppliers.[183] In this case a pure transactional approach regulates the suppler relationship. A white box approach, where all design work and related problem-solving is done by the buying company, is applied when the buyer owns in-house the design capabilities but does not possess manufacturing capabilities or if the outsource of the production results to be a more efficient solution.[184] A grey box approach is applied when the buying company aims to leverage technical capabilities and recognise suppliers as an important source of knowledge.[185] “Although suppliers have a relatively narrow knowledge base, buyers can easily access this knowledge base for product innovation. Other reasons for the positive effects of supplier collaboration on product

[176] See Petersen et al., 2005, p. 379
[177] See Petersen et al., 2005, p. 379
[178] See Petersen et al., 2005, p. 379
[179] See Möller & Törrönen, 2003, p. 110
[180] See Möller & Törrönen, 2003, p. 110
[181] See Möller & Törrönen, 2003, p. 110
[182] See Möller & Törrönen, 2003, p. 110
[183] See Möller & Törrönen, 2003, p. 113
[184] See Rosell & Lakemond, 2011, p. 7
[185] See Rosell & Lakemond, 2011, p. 8

innovation are related to the supplier´s expertise and comprehensive knowledge regarding the parts and components".[186] Both actors must also have complementary technological capabilities. "If their capability profiles are too similar, they have fewer opportunities for new knowledge creation than if their profiles are more specialised".[187] On the other hand, they must have a sufficient common ground that facilitates mutual learning processes. Companies with widely different processes and business systems have great difficulties in trying to coproduce value.[188] Finally, a black box approach is more appropriate when the buying company lacks the technical capabilities and does not consider the subsystem as a strategic focus. Schiele refers in this context to the purchasing of innovation, where the buyer commissions the development giving full responsibility to the supplier.[189]

In modular platform development the collaboration within a design network is possible only through coordination and alignment of component interfaces and design rules.

However, with regards to interfaces and design rules determination, two different types of business networks exist: centralised network and decentralised network.[190]

Centralized networks are those in which suppliers are tied to a lead company through strong vertical upstream integration, the design rules are laid down by the lead company, and they may differ from one lead firm to another. The lead company fulfils the role of systems architect and integrator.[191] By contrast, decentralised networks are characterised by loose integration of suppliers that have to meet the demands of diverse system-integrator customers and standards that are determined jointly by subsystem suppliers, integrators and, sometimes, final customers through market processes or negotiation. Since in decentralised networks the parties involved do not have sufficient bargaining power to force partners to adopt new interfaces and design rules nobody has exclusive control on it.[192] Thus, any attempt of standardisation may lead the companies to be isolated if other integrators and final customers do not follow their new interfaces and design rules.[193]

Most CoPS companies operate in such a decentralized network and rely on the design and development capacity of various suppliers. According to Hofman and colleagues "in such networks, it is hard to function as a lead firm, a systems architect, and introduce design rules for standardized product".[194]

[186] Rosell & Lakemond, 2011, p. 7
[187] Möller & Törrönen, 2003, p. 116
[188] See Möller & Törrönen, 2003, p. 116
[189] See Schiele, 2006, pp. 931-932
[190] See Hofman et al., 2009, p. 35
[191] See Hofman et al., 2009, p. 35
[192] See Hofman et al., 2009, p. 37
[193] See Hofman et al., 2009, p. 35
[194] Hofman et al., 2009, p. 35

The difficulty of standardising interfaces is also emphasised because of the project-based nature of the CoPS networks.

If interface standardisation and alignment is a crucial strategy in supplier involvement, it is also true that such an agreement can only be considered where the benefits exceed the costs.

A positive return on an investment is dependent on the size of the investment and the reuse potential modules related to that investment.

Therefore, components that have extensive variety in customer demands are better suited to non-integrated relationships and project-based procurement, whereas components with low variety demand are more appropriately delivered through integrated supplier relationships. Long-term multi-project production and large product volume are necessary to convince suppliers that the investment in components with new interfaces and design rules is justified.[195]

In the latter case, supplier involvement in new product development can be achieved through mutual long-term agreements on the allocation of future production orders to those suppliers who took part and responsibility in module development.[196]

According to Bonaccorsi and Lipparini three different approaches to the topic of the involvement of suppliers in new product development emerge as pure models: the “traditional,” the “Japanese,” and the “advanced” models.[197]

In the traditional model suppliers are involved after the design is completed and technical specifications defined. Thus the information disclosed by the leading firm is limited. The lack of explicit involvement in the early stages of the innovative process is normally joined with competitive procedures for supplier sourcing and selection. Suppliers are requested to quote a price and offer full technical and commercial conditions against technical specifications. In the pure competitive procedure, all potential suppliers are invited. However, this is not a necessary condition of the traditional model, since very often only pre-selected suppliers are invited to quote for the bid.[198]

In the Japanese model the involvement of suppliers normally takes place already in the design concept phase where suppliers join the firm’s meetings at the very beginning of the new product development process. Collaborative supplier relations are seen as the way to reduce time-to-market of the product and achieve sustainable long-term performance. Despite the benefits of this approach, selecting a single source at the very beginning of the development process would not allow the companies to capture new ideas emerging from other suppliers and lead the companies to incur in potential risk of extreme supplier reliance. [199]

[195] See Hofman et al., 2009, p.39
[196] Hofman et al., 2009, p. 40
[197] See Bonaccorsi & Lipparini, 1994, pp. 135-136
[198] See Bonaccorsi & Lipparini, 1994, p. 136
[199] See Bonaccorsi & Lipparini, 1994, p. 136

Finally in the advanced model the benefits of the Japanese model coexist with the access to new technical ideas and multiple sources of suppliers until the last stage of the product design. The advanced model appears to be the dominant approach in high-tech industries such as CoPS where a small group of preferred suppliers are involved in new product development before the definition of product specifications. They are requested to invest in development work in order to provide the company integrator with detailed technical solutions. Technical discussion meetings are regularly held, and all the invited suppliers are requested to demonstrate the performance of the components or subsystems they propose. In the advanced model, final supplier selection does not take place necessarily at an early stage of the new product development process. [200] All the invited suppliers are supposed to invest in the pre-selection development work, even if only one of them will win.

Each approach is potentially suitable for a new platform development process however their application and success may vary depending on the types of products and business environments.

Notwithstanding the importance of supplier involvement, companies seem to have only a limited understanding of how to include suppliers in new product (or platform) development. [201] According to Schiele, in project-driven product development “supplier integration has often been analysed without focusing on purchasing's role in this process”.[202] As a consequence, companies are more oriented to manage an existing project “rather than preparing the ground by selecting the right partners”. [203] Supplier sourcing and selection is a core responsibility of the purchasing function. The role of purchasing in new product development introduces the life-cycle perspective of purchasing that differs in key aspects from a R&D perspective.[204]

Purchasing professionals are expected to take a total cost-of-ownership perspective that extends throughout the product’s life cycle. [205] In platform development, platform design is only the first stage of the life cycle. Production and postponement are also important phases of platform‘s life cycle. [206] Although purchasing professionals should be included in development processes and platform teams, it is clear that purchasing managers who want to increase their department’s contribution to platform development teams “without neglecting company-wide obligations to control costs lack a model for this kind of orientation”. [207] In order to bridge this gap, Schiele proposed a model based on the dual role of the purchasing function. [208] The model makes a clear

[200] See Bonaccorsi & Lipparini, 1994, p. 136
[201] See Schiele, 2010, p.139
[202] Schiele, 2006, p. 928
[203] Schiele, 2006, p. 928
[204] See Schiele, 2010, p. 141
[205] See Schiele, 2010, p. 141
[206] See Schiele, 2010, p. 141
[207] Schiele, 2010, p. 141
[208] See Schiele, 2010, p. 146

distinction between the advanced sourcing function and the life-cycle sourcing function of procurement.

While the advanced sourcing team usually consists of engineers who have developed a strong technical background over time, the life-cycle team has a stronger commercial focus and is often responsible for a specific commodity within the company. [209]

According to Schiele, "segmenting the purchasing into advanced sourcing and life-cycle sourcing mirrors purchasing's dual cost and innovation-oriented role in new product development". [210]

2.5. An integrated planning and design methodology for platforms in CoPS

2.5.1. Introducing the platform planning and design process: a general process description

Ulrich defines product development as five-stage process consisting of concept development, system-level design, detailed design, testing and refinement and production ramp-up. [211] A platform development process is a deviation from the generic process.[212] The most important phase for a product development process based on a platform is the concept development phase. Concept development relies strongly on the platform strategy of the company. In fact, as described in 2.1.3, platform strategy gives the technological foundations of company's products and the core competences needed to develop the product platforms. Platform strategy should balance market alignment and market leverage in order to provide competitive advantage to the company. [213] In support of the platform strategy, Meyer and Lehnerd created a strategic segmentation grid that guides organisations to identify ways to leverage a platform and reuse common elements within a product family. [214] The early phase of concept development of platforms has been also defined by Robertson and Ulrich as platform planning.[215]

Bowman defines platform planning as "the proactive definition of an integrated set of capabilities and associated architectural rules that form the basis for a group of products".[216] Hence, the main objective of the platform planning process is to a find a platform solution that aligns key markets, customer requirements and underlying platform capabilities.[217] In this phase it is also important identifying those parts of the platforms that are more sensible to change in varying market requirements.[218]

---

[209] See Schiele, 2010, p. 146
[210] Schiele, 2010, p. 146
[211] See Ulrich and Eppinger, 1995, p. 15
[212] See Ulrich and Eppinger, 1995, p. 20
[213] See Bowman, 2006, p. 20
[214] See Meyer & Lehnerd, 1997, p. 39
[215] See Bowman, 2006, p. 20
[216] Bowman, 2006, p. 19
[217] See Bowman, 2006, p. 19
[218] See Martin and Ishii, 2002, p. 217

The second phase of the concept development conceived by Ulrich and Eppinger consists of generating platform concepts and select the platform concept which meets the platform requirements best.[219]In the development of a modular platform, the concepts selected should be analysed and modularised in order to generate decoupled components.[220]

Simpson and colleagues have gathered the works of more than thirty experts of the field to establish a common stream of literature of platform development.[221] Their work mostly aimed at bridging the gap between planning and managing platforms and designing and manufacturing them.

Development phase	Methodology	Author	Methodology Integration
Platform Planning	Market Segmentation Grid	Meyer & Lenherd (1997)	Simpson et al. (2012)
	Quality Function Deployment	Akao (1990)	
	Generational Variety Index	Martin & Ishii (2002)	
Platform Design	Coupling Index		
	Change Propagation Index	Suh et al. (2007)	
	Hierarchic layer Analysis	Hofer & Halman (2005)	

Table 2: Platform strategy, platform planning and platform design methodologies (own elaboration)

Different methodologies and processes have been conceived for platform planning and concept design. However many of the methods and tools have been developed in isolation from one another. Although Simpson and colleagues[222] proposed an integration of the most relevant methodologies, they did not include some design methodologies that are crucial for the purpose of this research: the CPI, CI and the HLA (see Table 2)[223]. The first measures the degree of physical change propagation caused by a component when an external change is imposed on the system[224], whereas the second helps engineering to identify reuse potential at different hierarchic layers of a system.[225]

[219] See Ulrich and Eppinger, 1995, p. 19
[220] See Martin and Ishii, 2002, p. 219
[221] See Simpson et al., 2012
[222] See Simpson et al., 2012
[223] Hofer and Halman, 2005, pp. 241-243
[224] See Suh et al., 2007, p. 73
[225] See Hofer and Halman, 2005, p. 241

2.5.2. Platform planning and design methodologies: Combining together distinctive methods

2.5.2.1. Market Segmentation Grid: segmenting the market according to the platform strategy

Meyer and Lehnerd introduced the MSG to support marketing and engineering identify potential platform leveraging strategies.[226] In the MSG market segments are listed on the horizontal axis, whereas price and performance segments are on the vertical axis (see Figure 6).

In the grid, four different leveraging strategies are identified: niche-specific platform, vertical leverage, horizontal leverage and beachhead strategy.[227]

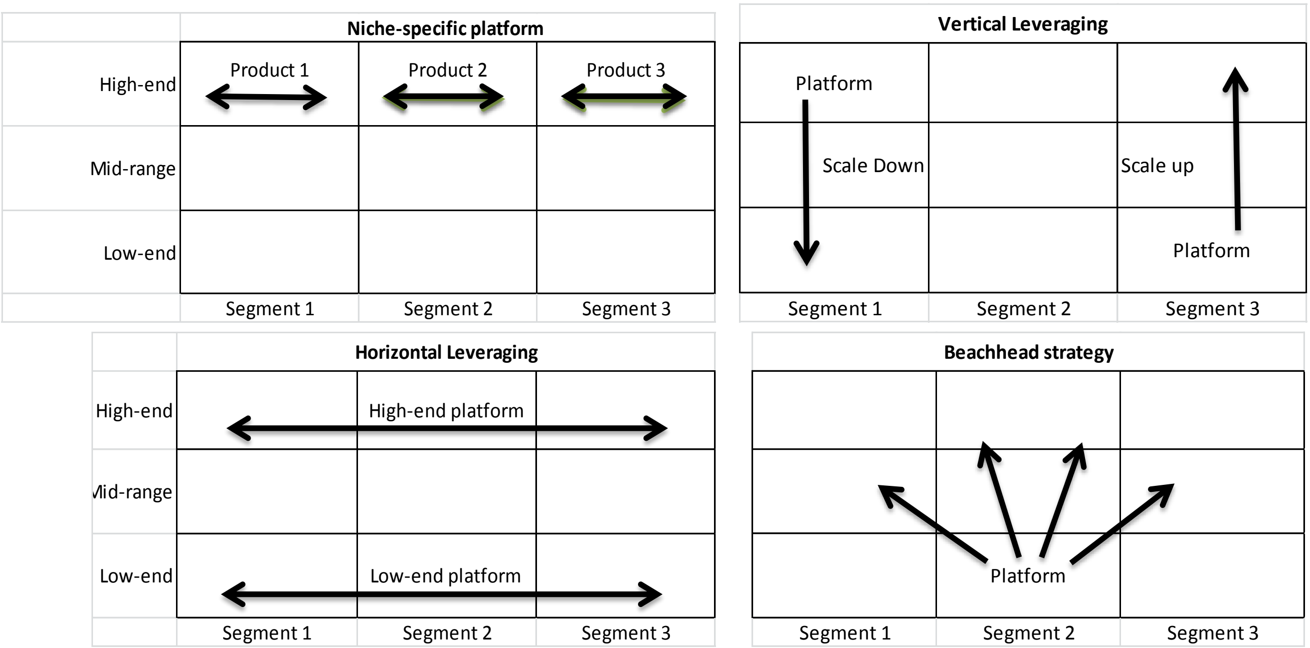


Figure 6: MSG based on Meyer & Lehnerd, 1997, p. 39)

Companies that follow the niche-specific platform strategy build a platform for each segment. The advantages of this strategy consist of the ease in building the segment platform and in the high level of specialisation of each platform. However, this implies high development and production costs. It is mostly applied when the differences in terms of requirements and products across the segments are very high.[228] The second platform strategy known as horizontal leverage is based on a common platform development for multiple segments. This approach guaranties learning effects and economies of scale. It enables companies to easily develop new variants and products from the same platform. The main difficulty in implementing this strategy is to find

[226] See Meyer and Lehnerd, 1997, p. 39
[227] See Meyer and Lehnerd, 1997, p. 39
[228] See Kleissl, 2004, p. 53

commonality across several market segments in order to serve them with the same platform.[229] In the vertical leverage strategy the platform can be scaled up or down according to the performance demanded. This facilitates companies to sell their products also to other lower-cost or higher-cost markets.[230]

Also for the vertical leverage there are advantages and disadvantages. Companies that implement this strategy develop a platform that can serve different performance and cost levels within the same segment. The last platform strategy is named beachhead strategy because of platform's flexibility to be optimised and adapted to serve different segments and levels of performance and cost. The initial basic platform is optimised to serve market and performance requirements of a specific segment. This is possible thanks to the scaling-up of the initial platform but also to the application, upgrade and exchange of platform functions. This strategy fits to those products that, even if complex, own and share a set of basic functions that can be scaled and adapted according to market and customer specifications.

2.5.2.2. Quality Function Deployment: transferring market requirements into technical specifications

QFD has been developed by Akao in Japan in the 1960's[231] and became very popular in the USA and Europe thanks to the orderliness QFD translates customer requirements into design characteristics for each stage of the product development.[232] The process aims at deriving quantified design and technical specifications from subjective qualitative data. Since the entire QFD process goes beyond the scope defined by Simpson and colleagues, the application of QFD is limited to the first two houses of quality.[233]

The first QFD matrix is used to translate the market requirements into technical attributes to which designers assign engineering metric target values (see Figure 7)

It begins with the determination of which market requirements will be analysed during the process and identifies which are the market segments. The platform and marketing teams gather and cluster information on the customer requirements that should be included in the platform. Current and future market requirements are related to technical specifications that express the functions of the platform.

Once the technical specifications of the platform have been identified, engineering metric target values are assigned to the technical specifications.[234]

---

229 See Kleissl, 2004, p. 54
230 See Kleissl, 2004, p. 54
231 See Akao, 1990, p. 8
232 See Gunzenhauser, 2007, p. 44-45
233 See Simpson et al., 2012
234 For the following description see Erzner, 2007, p. 12

	Engineering Metrics						
	Engineering Metric 1	Engineering Metric 2	Engineering Metric 3	Engineering Metric 4	Engineering Metric 5	Engineering Metric 6	Engineering Metric 7
Customer requirements							
Requirement 1	X						
Requirement 2		X					
Requirement 3			X				
Requirement 4				X			
Requirement 5					X		
Requirement 6						X	
Requirement 7							X

Figure 7: First QFD matrix (based on Martin and Ishii, 2002, p. 216)

In the second QFD matrix technical specifications and engineering metrics are mapped to the relative components involved in the design. An "X" indicates that the technical specification is related to the component (see Figure 8).[235]

	Components						
	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
Engineering Metrics							
Engineering Metric 1	X						
Engineering Metric 2		X					
Engineering Metric 3			X				
Engineering Metric 4				X			
Engineering Metric 5					X		
Engineering Metric 6						X	
Engineering Metric 7							X

Figure 8: Second QFD matrix (based on Martin and Ishii, 2002, p. 216)

From this exercise, those components and technical specifications that will form the baseline of the platform are identified. The main advantage of the QFD method lies in the systematic approach of collecting process and product requirements.[236] However, the original methodology developed by Akao does not offer any support in the field of customer-oriented variant planning and platform planning.[237] Hence, an integration of the QFD with other methods is needed.

[235] See Erzner, 2007, p. 13
[236] See Gunzenhauser, 2007, p. 46
[237] See Gunzenhauser, 2007, p. 46

2.5.2.3. Generational Variety Index: identifying the variable parts of the platform

The GVI is an indicator of the amount of redesign required for a component to meet the different and changing market requirements covered by the platform.[238] The platform strategy defines which market the platform will serve and how long the product platform is expected to last. Then market characteristics, norms and standards are identified and clustered according to the markets addressed by the platform.[239] According to the platform strategy and the differences in market requirements, multiple variants of the products are designated and will form the products families or derivative products based on the platform (see Table 3).

Rating	Description	Introduction date
Current Product 1	Initial design	January 2015
Future Product 2	Requires 15 % change	May 2015
Future Product 3	Requires 20% change	February 2016
Future Product 4	Requires 35% change	May 2017

Table 3: Product family plan (Martin and Ishii, 2002, p. 216)

This segmentation is used as a starting point for the GVI.[240] To generate the GVI, Martin and Ishii applied a modified version of the first QFD matrix. [241]

An additional column is added to the matrix and the variance of the market requirements is qualitatively estimated (high/medium/low). For example, “high” indicates that the market requirement highly varies from a customer or/and market region to another.[242]

The second part of this phase consists of estimating the expected changes across the products by assigning numerical metrics to the engineering target values (see Figure 9).[243]

The target values are generally based on both previous marketing data and future expected values. For the latters a scenario analysis could serve as a supportive method.[244]

The engineering metric (EM) target values provide the quantitative bandwidth that will be covered by the platform specifications. After the EM target values are identified, the platform team will use its engineering expertise to estimate the cost of changing components to meet the different EM target values of the specific specification (see Figure 9).[245] Following a rating system that assigns a continuum of values from 0 to 9, each component is ranked in order to

[238] See Simpson et al., 2012, p. 143
[239] Suh et al., 2007, p. 71
[240] See Martin and Ishii, 2002, p. 216
[241] See Martin and Ishii, 2002, p. 217
[242] See Martin and Ishii, 2002, p. 217
[243] See Martin and Ishii, 2002, p. 217
[244] For the subsequent description see Mietzner and Reger, 2005
[245] See Martin and Ishii, 2002, p. 218

define whether it is a variable component or a stable one across different EM target values (see Table 4).[246]

	Engineering Metric 1	Engineering Metric 2	Engineering Metric 3	Engineering Metric 4	Engineering Metric 5	Engineering Metric 6	Engineering Metric 7	Expected range of change in the platform
Market & Standards Requirements								
Requirement 1	X							H
Requirement 2		X						M
Requirement 3			X					L
Requirement 4				X				M
Requirement 5					X			M
Requirement 6						X		H
Requirement 7							X	M
EM target values	**kW**	**kW**	**V**	**m3/h**	**m3**	**dB**	**Kg**	**Start**
Current Product 1	35	20	400	2000	3	60	450	January 2015
Future Product 2	30	20	400	1600	2	66	600	May 2015
Future Product 3	25	35	400	2000	3	57	450	February 2016
Future Product 4	30	20	400	1600	2	66	600	May 2017

Figure 9: First QFD matrix with EM values added (based on Martin and Ishii, 2002, p. 216)

Rating	Description
9	Requires major redesign of the component (> 50% of initial redesign cost)
6	Requires partial redesign of components (< 50%)
3	Requires numerous simple changes (< 30%)
1	Requires few minor changes (< 15%)
0	No changes required

Table 4: GVI matrix rating system (Martin and Ishii, 2002, p. 216)

The GVI index is a good method for identifying the components that will be the core part of the platform and those parts that better suit modularised structures due to high GVI, consequence of expected recurring changes (see Figure 10). However, GVI analysis does not take into account the effects of component changes on other components.

[246] See Martin and Ishii, 2002, p. 218

Engineering Metrics	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
	Components						
Engineering Metric 1			1				6
Engineering Metric 2			1		3		
Engineering Metric 3							
Engineering Metric 4	3		3	6	6		
Engineering Metric 5	3						6
Engineering Metric 6			1		6		6
Engineering Metric 7	3						6
GVI	9	0	6	6	**15**	0	**24**

Figure 10: GVI calculation (based on Martin and Ishii, 2002, p. 218

2.5.2.4. Coupling Index: understanding how components are coupled and estimating their sensibility to change

The CI helps designers in understanding the coupling of the components within a platform architecture robust enough to meet different current and future market requirement. According to Ulrich, two components are considered coupled if a change made to one of the components can require the other component to change.[247] The stronger the coupling between components, the more likely a change in one will require a change in the other.[248] The CI is a process based on the DSM developed by Steward. [249] DSM has continuously grown in popularity and has been applied to many different fields of activity. In the case of product design and engineering, noteworthy examples are the NASA [250],Ford Motor Company [251] or Pratt &Whitney. [252] As the method has been the object of many studies in the fields of product design and project management, there is a plenty of variations of regarding DSM methodology and analysis. The CI process is a variation of the DSM method. The scope of the CI process is twofold:

1) Understanding the specifications flows between components;

2) Estimating the sensitivity of components to a small change in the specification.[253]

For instance, if a small change in the specification requires a change in the component, then the component has high sensibility.

The CI process is built on the components identified in the second house of quality of QFD. The components listed on both axes form the items of the CI matrix.[254]

[247] See Ulrich, 1995, p. 423
[248] See Martin and Ishii, 2002, p. 218
[249] For the subsequent description see Steward, 1981
[250] For the subsequent description see Brady, 2002
[251] For the subsequent description see Pimmler and Eppinger, 1994
[252] For the subsequent description see Sosa et al., 2003
[253] See Martin and Ishii, 2002, p. 218

Once the layout of the product has been depicted, for each component the control volume (CV) or engineering value of the component/component interaction is defined. Then, for each CV, the specification that is needed from each of the control volume to design the component is identified and listed.[255]

Rating	Description
9	Small change in a specification impacts the receiving component (high sensitivity)
6	Medium-high sensitivity
3	Medium-low sensitivity
1	Large change in the specification impacts the receiving component (low sensitivity)
0	No specification affecting component

Table 5: CI matrix rating system (Martin and Ishii, 2002, p. 220)

The top raw of the matrix lists the component supplying the information, whereas the left column the component requiring the information. At this stage, the sensitivity of each specification is assessed. For each specification, the team estimates the sensibility to each component to a small change in that specification.[256]

		Component SUPPLYING information			
		Component 1	Component 2	Component 3	**CI-R**
Component REQUIRING information	Component 1		CV x 3 CV y 3 CV z 1	CV x 3 CV y 9 CV z 1	20
	Component 2	CV x 9 CV y 3 CV z 3		CV x 3 CV y 3 CV z 1	22
	Component 3		CV x 6 CV y 1 CV z 3		10
	CI-S	15	17	20	52

Figure 11: CI matrix (based on Martin and Ishii, 2002, p. 220

[254] See Martin and Ishii, 2002, p. 218
[255] See Martin and Ishii, 2002, p. 219
[256] See Martin and Ishii, 2002, p. 219

Table 5 shows the ranking system used to estimate the sensibility to change. The CI is then calculated for each component and the most critical parts having the highest CI are identified (see Figure 11).[257] While the components that have the lowest CI rating can be standardised or partially standardised, the most critical components will be modularised.[258] Although the CI process helps to understand the complex specifications between components and to identify those components that have the highest coupling, however, it does not provide a solution for reducing the coupling and modularising the component.

2.5.2.5. Change Propagation Index: estimating component sensibility to changes in technical specifications

The CPI indicates the strength of coupling between system components. It measures the degree of physical change propagation caused by a component when an external change is imposed on the system.[259] According to Ulrich, two components are considered coupled if a change made to one of the components can require the other component to change.[260] The stronger the coupling between components, the more likely a change in one will require a change in the other.[261]

The CPI is a process based on the DSM developed by Steward.[262] DSM has continuously grown in popularity and has been applied to many different fields of activity. In the case of product design and engineering, noteworthy examples are the NASA[263], Ford Motor Company[264] or Pratt &Whitney.[265] Since DSM has been the focus of many studies in the fields of product design and project management, there is a plenty of variations of regarding DSM analysis. The scope of the CPI is to identify the most critical components in terms of sensibility to change in the specifications. Figure 12 shows that within the system, there are seven components connected to each other. They can be connected physically (e.g. welded together), or through information (e.g. signals), energy (e.g. electrical power) or material flow. The DSM represents the system using a matrix format with 1's indicating connectivity between elements.[266]

The matrix is useful because helps designers to identify system components affected by changes in the requirements and to observe the change propagation to other components when a change in the specification is needed.[267]

---

[257] See Martin and Ishii, 2002, p. 220
[258] See Martin and Ishii, 2002, p. 223
[259] See Sue et al., 2007, p. 73
[260] See Ulrich, 1995, p. 423
[261] See Martin and Ishii, 2002, p. 218
[262] For the subsequent description see Steward, 1981
[263] For the subsequent description see Brady, 2002
[264] For the subsequent description see Pimmler and Eppinger, 1994
[265] For the subsequent description see Sosa et al., 2003
[266] See Sue et al., 2007, p. 73
[267] See Sue et al., 2007, p. 73

The top raw of the matrix lists the component propagating the change, whereas the left column the component receiving the change.[268]

Once the matrix is constructed, the sensitivity of each specification is assessed. For each specification, the team estimates the sensibility of each component by assigning "1" when a component receives from or propagates change to other another component.[269]

The terms multiplier, carrier, absorber, and constant have been defined by Suh and colleagues to classify elements that react to changes.[270]

		Component PROPAGATING change							
		Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7	ΔE in
Component RECEIVING change	Component 1				1	1	1	1	4
	Component 2					1	1		2
	Component 3							1	1
	Component 4	1				1		1	3
	Component 5	1			1		1		3
	Component 6	1			1	1			3
	Component 7			1					1
CPI	**ΔE out**	3	0	1	3	4	3	3	
	CPI	**-1**	**-2**	**0**	**0**	**1**	**0**	**2**	
	Class CPI	**A**	**A**	**C**	**C**	**M**	**C**	**M**	

Figure 12: CPI calculation (based on Suh et al., 2007, p. 74)

Multipliers are elements that ‘‘generate more changes than they absorb.’’ Carriers are elements that ‘‘absorb a similar number of changes to those that they cause themselves.’’ Absorbers are elements that ‘‘can absorb more change than they themselves cause.’’ Finally, constants are elements ‘‘that are unaffected by change’’.[271] Focusing on multiplier and carrier components, the platform team should find solutions aimed at reducing or even eliminating change propagation altogether.[272]

2.5.2.6. Hierarchic Layer Analysis: selecting design concepts, designating predefined and variable components, stabilising platform architectures

Hofer and Halman introduced the hierarchic layers of a product architectures by stressing the difference between reuse of components and architectures. They claim that the variation of defined components usually result in limited changes to the overall system, whereas the changing

[268] See Sue et al., 2007, p. 74
[269] See Suh et al., 2007, p. 73
[270] See Suh et al., 2007, p. 73
[271] See Suh et al., 2007, p. 73
[272] See Suh et al., 2007, p. 73

of a system layout causes potentially higher complexity in the following layers of the product architecture (see Figure 13).[273]

The first layer of the product architecture describes the predefined features and components that form the basic components of a subsystem- i.e. the product platform. The second layer refers to the variable components and functions of the subsystems. These first two layers define the subsystems, which are arranged in a system layout (third layer). The integration of these subsystems to system's level is done in the fourth layer of product architecture.[274]

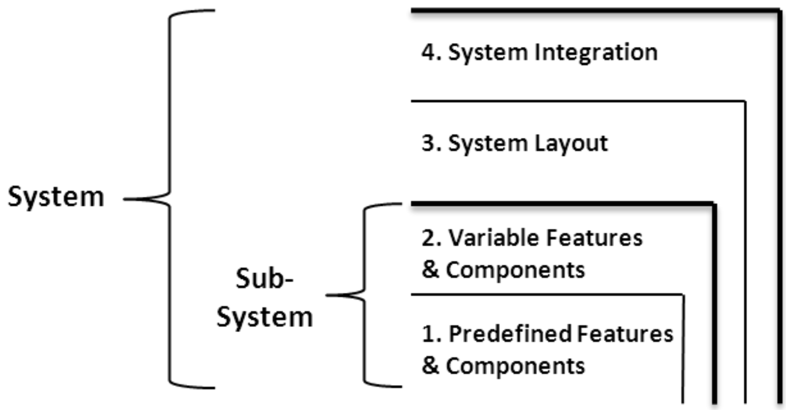


Figure 13: Hierarchic layers of the system architecture (based on Hofer & Halman, 2005, p. 242)

According to Hofer and Halman the separation of different hierarchical layers distinguishes components, concepts and integration methods of the product architecture.[275] This framework helps engineering to define platform potential for each hierarchic layer of the product architecture.

[273] See Hofer and Halman, 2005, p. 242
[274] See Hofer and Halman, 2005, p. 242
[275] See Hofer and Halman, 2005, p. 242

2.5.3. Methods evaluation: Assessing the planning and design methodologies

Notwithstanding some methodologies like the MFD [276] or various software-based modularisation methods[277] are not considered for a matter of relevance and simplicity of their application, the planning and design methodologies described above represent the state-of-the-art in platform planning and design methodologies. The aim of this research is to combine these methodologies in order to achieve an integrated platform planning and design methodology. In chapter 2.4 the main platform development characteristics and background knowledge are described. According to this information, seven major tasks that should be fulfilled by a comprehensive platform planning and design methodology were identified.

	MSG	QFD	GVI	CI	CPI	HLA
Market segmentation	Covered	Not covered	Partially covered	Not covered	Not covered	Not covered
Market requirement capture	Not covered	Partially covered	Partially covered	Not covered	Not covered	Not covered
Technical specification capture	Not covered	Covered	Partially covered	Not covered	Not covered	Not covered
Planning for variety	Partially covered	Not covered	Covered	Partially covered	Partially covered	Partially covered
Design for changeability	Not covered	Not covered	Not covered	Partially covered	Partially covered	Partially covered
Modularisation	Not covered	Not covered	Not covered	Not covered	Not covered	Partially covered
Joint platform design	Not covered	Not covered	Not covered	Not covered	Not covered	Not covered

Not covered Partially covered Covered

Table 6: Cross-comparison matrix of the methods (own elaboration)

[276] For the following description see Erixon, 1998
[277] For the following description see Simpson et al., 2014

Table 6 shows to what extent the tasks are covered by the methodologies described in the previous chapter, whereas below an assessment of the methodologies is provided.

MSG: The MSG is a good method to represent the strategy used to address different market segments by optimising and leveraging the initial platform. However, in the product family literature, the MSG has only been used as visual aid to arrive at the appropriate platform leveraging strategy.[278]

QFD: The main advantage of the QFD method lies in the systematic approach of collecting process and market requirements as well as translating them into technical specifications.[279] However, the original methodology developed by Akao does not offer any support in the field of variant planning and platform planning.[280] Hence, an integration of the QFD with other methods is needed.

GVI: The GVI index is a good method to identify the components that will be the core part of the platform and those that better suit modularised structures due to high GVI, consequence of expected recurring changes (Planning for variety). The main strength of the method is also that it manages to combine platform segmentation and QFD. However, GVI analysis does not take into account the effects of component changes on other components and modularisation of components.

CI: Martin and Ishii proposed a good combination of the GVI method to the CI.[281] Although the CI process helps engineers to understand the complex specifications between components and to identify those components that have the highest coupling, it does not provide any support for reducing the coupling and modularising the component. Furthermore, the first part of the method is very time consuming and goes too much in details for a concept design phase.

CPI: The method offers a simple and practical approach to identify the components that are more sensible to internal changes. It is a good alternative to the CI because it does not identify the type of specification between components in details but focuses only in the identification of the drivers of internal variety. Although the CPI is a good starting point to define the focus of modularisation, it does not offer an operative support to the modularisation activity itself.

---

[278] See Kumar et al., 2006, p. 8
[279] See Gunzenhauser, 2007, p. 46
[280] See Gunzenhauser, 2007, p. 46
[281] See Martin & Ishii, 2002, p. 219

HLA: The method helps engineering to differentiate between different hierarchical layers of the system and identify reuse potential at different layer level. Furthermore, HLA provides a framework to reduce coupling and standardise interface of the system that is a crucial modularisation activity.

Although every method described does not forbid internal engineers to collaborate with external parties such as suppliers no methodology for joint platform design has been found in the literature. As consequence a possible solution will be investigated in the case studies.

2.6. Towards platform planning and design in rail rolling stock: CoPS as a starting point

As shown in 2.3.1 CoPS are a particular research area that includes several industries and various distinctive products. Railway rolling stock is included in this categorisation since they can be identified with the general definition of CoPS: “high-technology, high-value capital goods that are software and engineering intensive”.[282] Rolling stock can be clustered in three main product segments: locomotives, passenger rail vehicles and freight wagons.[283] In turn, each segment includes different types of product (see Figure 14).

Rolling stock has multiple CoPS characteristics at product and product development level. They are designed and developed within a product development project that is often initiated and driven by governmental and institutional customers.[284] Since rolling stock product development is usually driven by quite detailed customer requirements, the level of customisation is very high.[285] Rolling stock providers act as system integrators within projects that generally involve several subsystem and component suppliers as well as customer and national authorities. This explains the large quantity of components and subsystems integrated into a rolling stock system and often developed *ad hoc* for every single project.

In single-product development design rules differ from a customer to another and are highly influenced by regulations and standards in different countries.[286] For instance, regulation in the railway industry, due to historical reasons, has been mostly dominated by the preservation of its

[282] See Davies & Hobday, 2005, p. 8
[283] See SCI Verkehr, 2014, p. 2
[284] See Davies & Hobday, 2005, p. 8
[285] See Davies & Hobday, 2005, p. 8
[286] See Pellegrini & Rodriguez, 2013, p. 71

national character. For years it was considered the key factor governing the overall regulation within the industry.[287]

As a result great differences exist in terms of operational standards, railway infrastructures and technical solutions.[288] Fairly universal, reliability, safety and in-time delivery are regarded as the main attributes that are perceived to create value to the customer. These factors directly and indirectly lead to high development and testing costs. Furthermore, it seems that customers demanding for high reliability whilst at the same time demanding lower costs are going to further increase by the year 2020.[289]

Since rolling stock may be perceived as CoPS, a similar potential to develop modular platforms for rolling stock exists and is confirmed by the increase of standardisation and modularisation trends within the railway industry.[290]

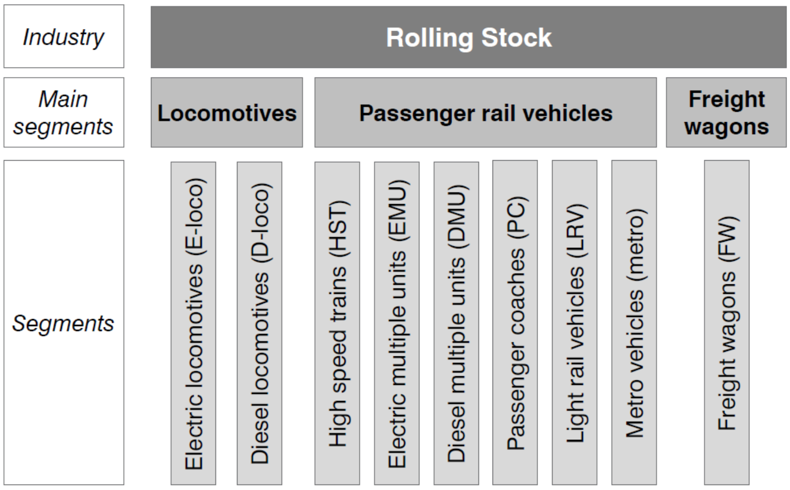


Figure 14: Rolling stock classification (SCI Verkehr, 2014, p. 2)

However, the rolling stock providers that aim at shifting towards a platform-based product development, similarly to CoPS, have to deliberatively restrict and predefine the platform architecture of rolling stock through the support of the planning and design methods described in the previous chapter.

Although rolling stock has most of CoPS characteristics, additional contingent aspects that are specific to the rolling stock industry and rolling stock may be identified. This may lead to additional platform planning and design characteristics, including correlated methods that are specifically tailored to rolling stock.

Hence, the case studies investigated in this research aim at verifying whether rolling stock shares the same platform planning and design characteristics of CoPS.

287 See Campos & Cantos, 1998, p. 9
288 See EMCC, 2004, p. 6
289 See Railway Gazette International, May 2013, p. 106
290 See UNIFE, 2012, p. 63

3. Bombardier Transportation - global rolling stock provider aims at developing modular platform-based products

3.1. Global organisation grown mainly through acquisitions - shaping the organisational structure to enforce centralised strategy and guidance

BT is a world leader in the design, manufacture and support of rail equipment and systems. It is part of Bombardier Inc. that also includes Bombardier Aerospace, a leading corporation in the aircraft market. In 2013 BT generated revenues of 8.8 billion euro and employed more than 38.500 employees all over the world.[291] Since a recent restructuring activity the company is organised in four regional divisions, three core value chain functions, two global businesses and the group headquarters. Since June 2013 Dr. Lutz Bertling is the COO of BT. While the BT headquarters is located in Germany, the aerospace subsidiary has its headquarters in Canada. The company was indeed funded by Joseph-Armand Bombardier in Canada in 1941 and started its business in the production of snowmobiles for the Canadian market.[292] After the entrance in the Canadian aerospace market, in the mid-1970s Bombardier started its expansion into the manufacturing of metros and other rail vehicles.[293] Through a combination of astute acquisitions and organic growth, BT has established 59 production and engineering sites in Europe, North and South America, South of Africa and Asia. [294] Nowadays BT does not only produce rail vehicles, but also complementary equipment such as rail control and signalling as well as train subsystems like bogies and propulsion systems. It takes over also maintenance services and fleet management along the entire product lifecycle.[295]

Focusing on the European market, after the begin of deregulation and liberalisation of the railways started in the 1990s[296] BT begun a series of mergers and acquisitions that brought the company to acquire two European leading rail manufactures, the French ANF-Industrie and the German Adtranz as well as other smaller rolling stock providers. On one hand the strategic acquisitions added precious value to BT's expertise and competiveness but on the other its growth trajectory increased the decentralised structure of the company and the variety of engineering sites.[297] Strong decentralisation, diverse technical skills and the consequent increase of tailored products in the product portfolio have provoked not few integration efforts across the various engineering and production sites, in particular in the execution of large cross-regional projects.[298] In the beginning of 2014, the company launched the "*OneBT*" strategy in order to align the divisions and to start harmonisation and standardisation of products, systems, processes

[291] See BT-Doc, 2014a
[292] See MacDonald, 2013, p. 27
[293] See MacDonald, 2013, p. 27
[294] See BT-Doc, 2014a
[295] See BT-Doc, 2014b
[296] See UNIFE, 2012, p. 61
[297] See BT-Doc, 2014c
[298] See BT-Doc, 2014d

and tools.[299] One important aspect of the new strategy consists of reshaping the corporate organisational structure to facilitate better coordination and performance across the sites. Until 2013 the company was structured in six decentralised divisions, excluding the headquarters. Each division worked independently with very low coordination and strategic alignment, often increasing the size of the product portfolio without being capable of reusing existing solutions.[300]

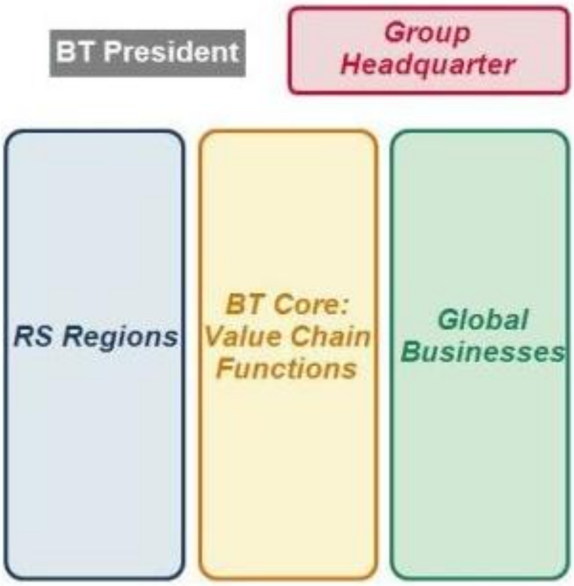


Figure 15: OneBT organisational structure (BT-Doc, 2014e)

In order to invert these trends, the new organisational structure includes the creation of the BT core value chain functions that are responsible to support the Regions in the supply chain (GSC), technology (CTO) and project management (Group Project management) guidance of the regions. The Regions are now divided into four geographical areas: Western Europe Africa and Middle East, Central and Eastern Europe, Asia Pacific and Americas. Finally, the global businesses are two independent units formed by the rail control and signalling unit and system integration unit (see Figure 15).[301]

[299] See BT-Doc, 2014d
[300] See BT-Iben, 2014a
[301] See BT-Doc, 2014e

3.2. A changing business environment: the need of new product development strategies to remain competitive

3.2.1. Turbulence and fierce competition in the rolling stock industry: the rise of new entrants, the decline of the incumbents

The industry of worldwide rolling stock manufactures is sailing in rocky water. The increasing liberalisation of the European Market allows Asian companies and other foreign companies to expand into Europe.[302]

New entrants such as the Chinese manufactures CNR and CSR, the Swiss Stadler and the Russian Transmashholding tremendously increased their sales and established themselves among the largest and most profitable manufactures over the world.[303]

The high growth of the new entrants created issues for other competitors. For instance, CAF, Hyundai Rotem and Kawasaki slipped out of the top ten worldwide manufactures even though they showed good financial results in 2012.[304] The market dominance of BT, Alstom and Siemens received a bitter setback. In 2011 BT after years of uncontested leadership in the market lost the first position in the ranking of the top ten global manufactures, slipping to the third place.[305] The Chinese corporations gained the first two positions of the ranking thanks also to the favourable conditions of the Chinese market that, contrary to the European market, is not liberalised yet.[306]The new balance of power is showed in the sales number of 2012 (see Figure16). Although the state-owned Chinese enterprises CNR and CSR mainly grew thanks to the boost of a domestic market protected from foreign competition, they are nowadays undoubtedly identified as the new leaders of the worldwide industry of rolling stock manufactures.[307]

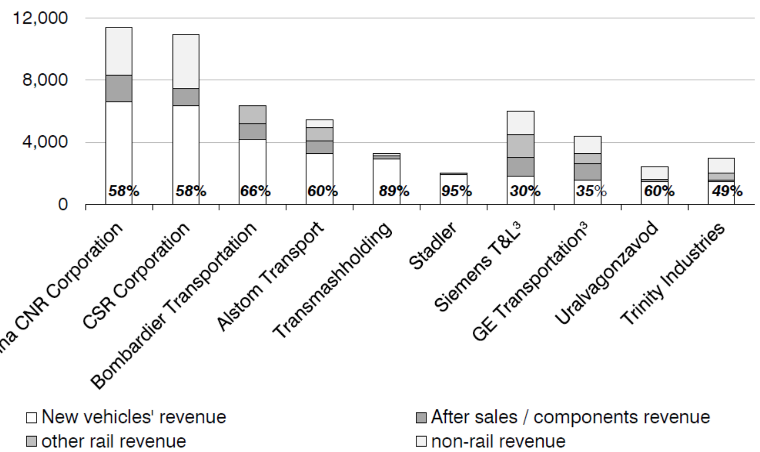


Figure 16: 2012 sales of the top ten worldwide rolling stock providers (SCI-Verkehr, 2014, p. 5)

[302] See Roland Berger Strategy Consultants, 2012, p. 61
[303] See SCI Verkehr, 2014, p. 5
[304] See SCI Verkehr, 2014, p. 6
[305] See SCI Verkehr, 2014, p. 6
[306] See UNIFE, 2013, p. 39
[307] See Adachi, 2013, p. 10

A general overview of the industry shows that the ten most important manufacturers generated combined new vehicle revenues of around € 13 billion, representing 65% of the global market for new vehicles.[308] The twenty largest manufacturers already account for almost 85% of the total market for new rail vehicles. However, the other players that account for 15% of the global market share may take advantage of leveraging small projects and pose serious competitive threat to the incumbent companies.[309] This high degree of competition is confirmed by decreasing profit margins among the globally active companies. BT, Alstom and Siemens are subjected to a constant decline of their EBIT margins that was between 3% and 7% in 2012, which is significantly under the average of the rising new entrants.[310]

Although standardisation strategies and platform concepts may conflict with the increasing demand of customised rail products, it may be the only way for the incumbent players to catch up with the new entrants.[311] If rolling stock providers desire to remain competitive, they have no choice but to improve their performance by reducing development and purchasing cost as well as speeding up the time-to-market of their products.

3.2.2. Entering new markets: increasing variety and complexity of customer requirements

Despite the recent economic crisis, many countries have added rolling stock and rail infrastructure kilometres to their network. The worldwide railway network has now reached more than 1.6 million kilometres that represents more than 40 times the circumference of the earth. More than 5.2 million units of rolling stock are deployed in this network, creating great business opportunities for the global rolling stock manufactures.[312] The railway network has been tremendously increasing mainly because of the continuous expansion of the emerging countries that keep on growing above the average of the mature economies.[313]

Developing countries are investing big capitals in both rail products and infrastructures in response to increasing urbanisation and demand of efficient mass-transport systems. By contrast, the developed markets are experiencing slow growth due to their saturated markets and the high deficit and debts inherited by the long financial crisis.[314]

As a consequence of this two-speed world, it is highly likely that the focus of the railway market will shift from the Western countries to Asia, Latin America and Africa. Rapid growth in Latin

[308] See SCI Verkehr, 2014, p. 5
[309] See Roland Berger Strategy Consultants, 2012, p. 22
[310] See SCI Verkehr, 2014, p. 5
[311] See UNIFE, 2012, p. 62
[312] See UNIFE, 2010, p. 7
[313] See UNIFE, 2010, p. 6
[314] See UNIFE, 2010, p. 6

America, Middle East and parts of Africa are showed by the forecasts of investment growth in the rolling stock industry for 2015 to 2017 (see Figure 17)[315]

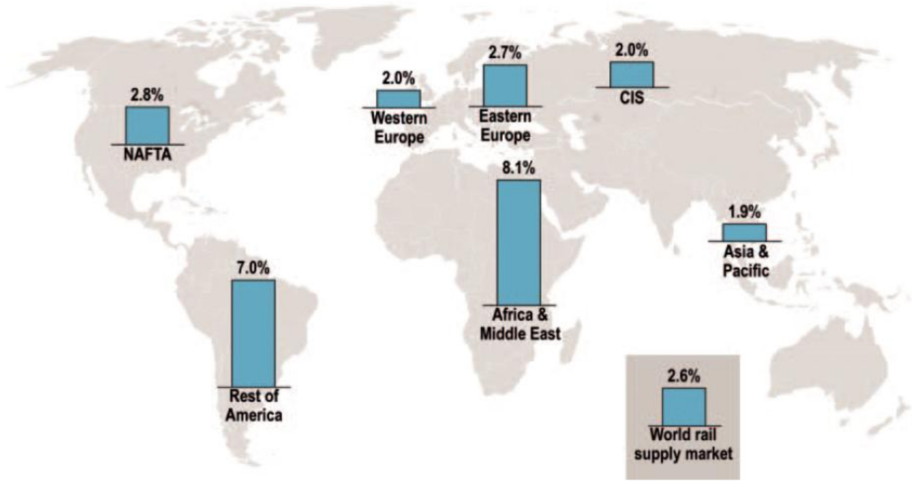


Figure 17: Forecast regional growth average rates in the rolling stock market between 2015 and 2017 (UNIFE 2012, p. 10)

Emerging markets are becoming more accessible to European rolling stock manufactures, however, the variety of markets, standards, infrastructures as well as customer preferences and needs result in difficulties and risks in managing their global product portfolio. The increasing complexity experienced by global rolling stock manufactures in managing their expanding product portfolio is not yet mitigated by the efforts of the EU to improve rolling stock interoperability. [316] Notwithstanding the European policies aiming at harmonising the different national railways with a common ERTMS, higher degree of customer involvement in rolling stock projects keeps on limiting the success of European policies[317] This is explained by the strong active role of customers such as DB in Germany or SNCF in France in defining the technical specifications, a consequence of their long-lasting experience in the industry.[318] The increasing variety of market requirements specifications and the increasing demand of customised rolling stock in Europe requests global rolling stock manufacturers to implement platform and modularisation strategies aimed at reducing the complexity of their product portfolio.[319]

---

[315] See UNIFE, 2012, p. 10
[316] See UNIFE, 2012, p. 62
[317] See UNIFE, 2012, p. 62
[318] See BT-Iben, 2014b
[319] See Railway Gazette International, July 2014, p. 40

3.3. Is modularity of platforms the solution for BT to remain competitive?

Both the decentralised organisation and the numerous BT production and engineering sites worldwide sites, result in a heterogeneity of engineering skills, manufacturing process and component suppliers. The turbulent business environment characterised by increasing competition and heterogeneity of customer demands leads to the same solution: If BT wants to improve its operating performance, remain competitive and enter new markets whilst managing its product portfolio risk, it should shift to platform and modularity-based strategies. This is also demonstrated by the following analysis of BT using Shilling's casual model explaining the "General modular system theory" introduced in 2.2.3.[320]

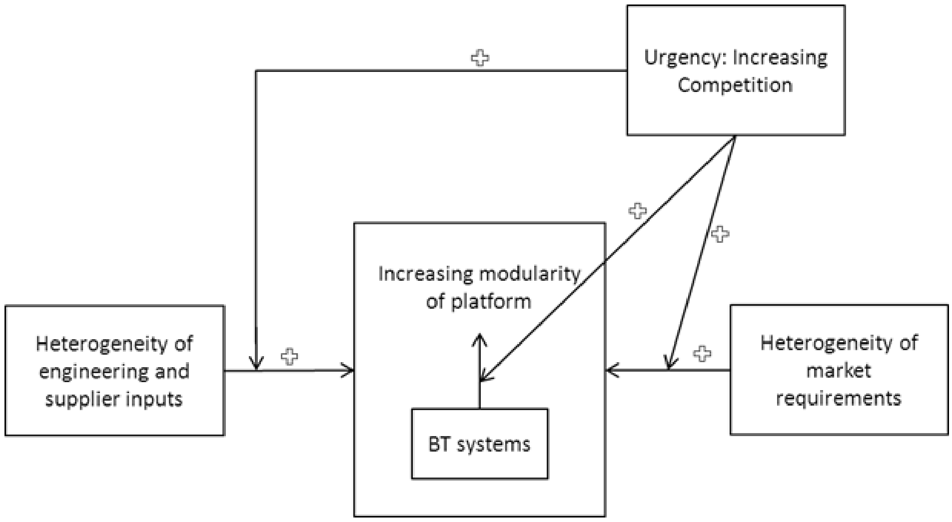


Figure 18: Casual model representing BT systems migration towards modularity (based on Schilling, 2000, p. 319)

According to Schilling, the heterogeneity of both inputs and demands increases pressure for companies to develop modular systems, and both reinforce the effect of the other. Furthermore, factors creating urgency in the context can catalyse system's response to the balance of these forces.[321] In other words, companies such as BT that have to cope with a lot of different engineering and supplier inputs in order to deliver an increasing variety of products to distinctive markets are forced to develop modular systems at the expense of integral systems. The higher the urgency driven by increasing competition, the faster the shift towards a modular product development will be. Figure 18 above shows Shilling's model adapted to BT scenario.

[320] See Schilling, 2000, p. 319
[321] See Schilling, 2000, p. 318

3.4. Moving from product development project to platform development: Learning from previous platform-based projects

BT´s product development process consists of the planning, design, realisation and delivery of rolling stock products (see Figure 19). The main product development activities are executed within a project and generally driven by customer requirements.[322] Customer requirements are the result of the bid process. It starts with the invitation to tendering to rolling stock providers and concludes with the discussion and the negotiation of customer specifications with selection of the provider. For each bid, BT designs a vehicle or adapts an existing product to the usually quite detailed customer requirements.[323]

Hence, the design and sourcing activities are mostly customised to the specific project. Such a high level of customisation as well as BT´s worldwide distribution over 59 production and engineering sites makes reuse across sites very difficult. [324]

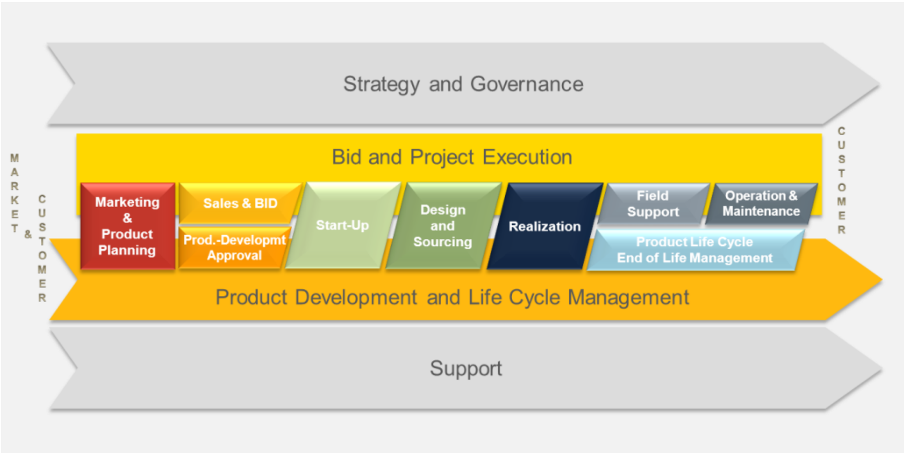


Figure 19: BT landscape product development process and project (BT-Doc, 2014g)

The combination of both factors led BT to experience an extreme amount of hours spent in parallel product developments. [325]

Although in the past BT recognised the need of moving to standardisation and harmonisation of its multi-project product portfolio, in the implementation process many obstacles impeded the change. For many years the reuse "strategy" consisted of seeking to adapt previous projects in order to meet new customer requirements. Sometimes potential for reuse was identified "by accident" after explicit requests by customers such it was the case for DB and *TRAXX* locomotives.[326]

[322] See BT-Iben, 2014a
[323] See BT-Iben, 2014a
[324] See BT-Doc, 2014f
[325] See BT-Doc, 2014f
[326] See BT-Iben, 2014b

Only some divisions managed to increase reuse across projects through the development of standardisation and platform solutions. For instance, LRV developed the *Flexity2* a product platform that helped BT to achieve and maintain the leadership in the global LRV market.[327] In a relative short period of time the *Flexity2* family became the benchmark for urban mobility in many countries around the world.[328] Similarly, LOC developed different product evolutions of the original *TRAXX* platform that for years dominated the European market of electric and diesel-electric locomotives for freight and passenger services.[329]Last but not least, the *Aventra* platform, a three-year intensive development project to create a step change in train technology meeting the UK market requirements for innovative and high performance generations of electric multiple units and metros.[330]

Even though limited by the regional requirements and standards of North America, the *Bi-Level* platform triggered the standardisation activities in North American. BT has been building *BiLevel* commuter trains for the North American market for more than 25 years. With the input of customers, the *BiLevel* platform re-engineered the manufacturing process of the American engineering sites by enabling the use of common product architectures.[331] Notwithstanding the previous platform developments were limited to the division-focused business and, sometimes, to single markets- i.e. Aventra for the UK market or BiLevel for Canada and some USA states- however, their solutions, especially in terms of processes and engineering inputs became precious lesson learned.

3.5. Modular platforms at BT: Making it happen through the guidance of the CTO

In the end of 2013, to launch the corporate strategy of standardising and innovating its products while at the same time being cost effective, BT created a new mandate for the core value chain function CTO.[332] The mandate of CTO is to promote and enable reuse and standardisation of products, technical concepts and engineering processes in order to increase the overall competitiveness and form the basis for a future platform and module-based product portfolio.[333] CTO consists of four Platform units and also the Research and Technology unit, the Specialist Engineering unit and the Engineering Management Office/ Quality. The four platform units are Vehicles Platforms, Subsystems Platforms, TCMS and Services Platforms (see Figure 20). Since Vehicles platforms are responsible to develop platform strategies at vehicle level, they were selected as main focus of analysis of this research (see Figure 21).

---

[327] See BT-Doc, 2009
[328] See BT-Doc, 2009
[329] See BT-Doc, 2013
[330] See BT-Doc, 2011
[331] See BT-Doc, 2007
[332] See BT-Doc, 2014h
[333] See BT-Doc, 2014h

The long-term strategy of CTO is to develop modular vehicle platforms that shape the basis for competitive products, allowing fast execution based on predefined modules, architectures and design solutions.[334] Such a challenging strategy has been pursued in parallel with a short-term strategy, called "quick-win strategy". It consists of allowing and ensuring re-use of the many proven solutions that have were developed in the previous projects. [335] The Inventory taking" activity aims at identifying potential for reuse and standardisation within the product portfolio, Vehicles platforms involved also the other platform units and the regions to close collaborate through the "Inventory taking" that represented the first big step of the company towards modularisation and standardisation (see Annexure 7). [336]

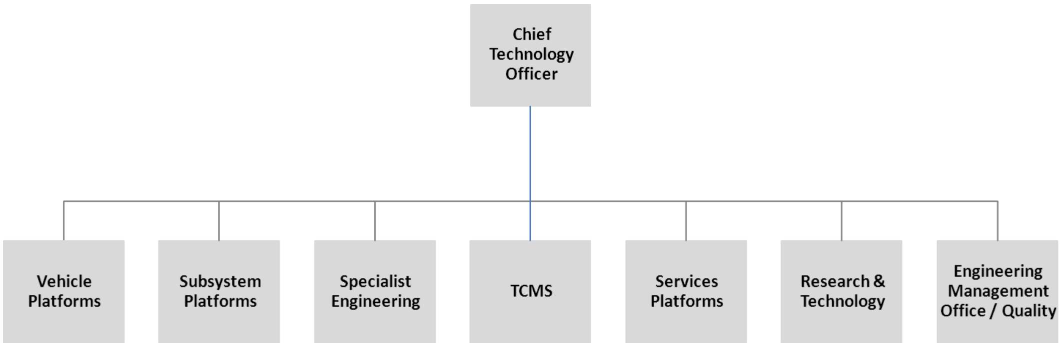


Figure 20: CTO organisational chart (BT-Doc, 2014e)

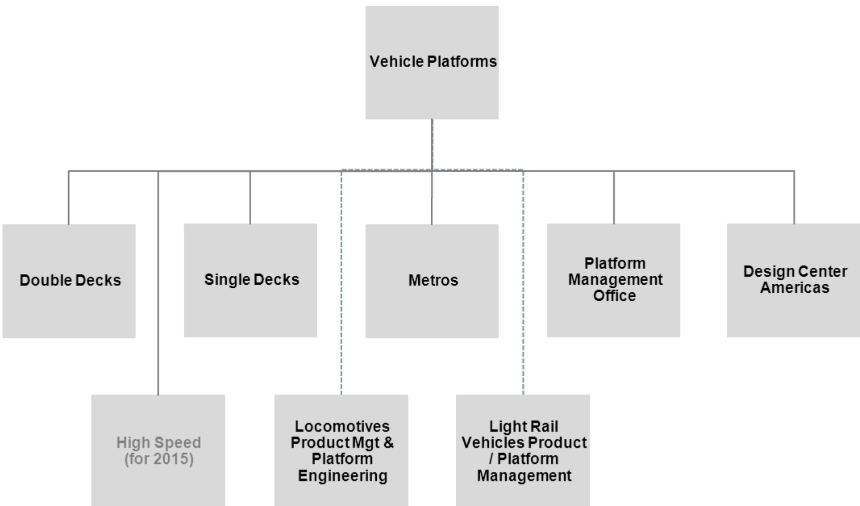


Figure 21: Vehicles Platforms organisational chart (BT-Doc, 2014e)

[334] See BT-Doc, 2014h
[335] See BT-Doc, 2014i
[336] See BT-Doc, 2014i

Vehicle Platforms set the challenge to completely abandon its “flawless project execution” and to put in place the development of modular platforms. This consists of the development of standardised parts and modules that can be easily integrated and adapted to project-specific vehicles in a worldwide market.[337]

For 2014 and 2015 the two main goals of Vehicles Platforms in joint collaboration with Subsystems platforms and TCMS are:[338]

1) Create a library of technical solutions that can be easily reused in new platform development projects.

2) Plan and design a first rail vehicle platform as lighthouse for the other vehicle platforms.

The second task, that is the focus of this thesis, seems to be a challenge for an organisation that, in the exception of some areas, has always operated through single-product development projects. Hence, it is important for platform managers and design engineers to understand the main platform planning and design characteristics to apply them in the new platform-based projects.

To conclude, in light of the challenges deriving from the changing environment in which BT operates, platform and modularisation strategies led by the CTO represent the inevitable direction to follow in order to ensure a long-term competitive advantage.

To accomplish this goal, a primary task that will be pursued by the company will consists of identifying the platform characteristics, including the relative planning and design methodologies.

[337] See BT-Doc 2014h

[338] See BT-Doc 2014h

4. Combining theory-based problem solving and case study research

4.1. Theory-based business problem solving: a framework to link theory and practice for problem solving within an organisation

This thesis aims to explore and provide solutions to the difficulties experienced by multinational organisations that operate in the rolling stock industry and that want to develop modular platforms through planning and design methodologies tailored to their business needs. This problem directly emerges from practice and relates to the business context of BT. However, this academic work also needs to satisfy scientific rigour of a research assignment. To comply with both prerequisites of relevance in practice and academic research this thesis applies the business problem-solving methodology developed by van Aken and his colleagues.[339] The reason why this approach is perfectly suitable to the case of BT is twofold. Firstly, as claimed by the author, this method lays on a strong theoretical foundation, using state-of-the-art literature.[340] Secondly, it applies very well to business problems that have significant technical and economic components.[341] While the first requirement has been fulfilled by the comprehensive literature used in the second chapter, the second requirement fits perfectly to the concepts of platform and modularity applied within BT.

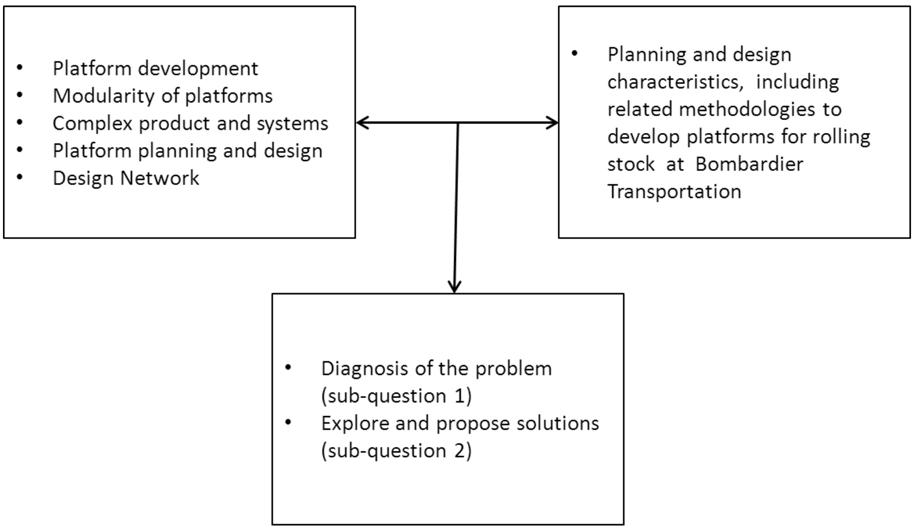


Figure 22: Conceptual model (based on van Aken et al., 2007, p. 51)

Figure 22 above shows the conceptual model developed by van Aken and colleagues to visualise the methodological process, here adapted to the business problem covered in this research work. While the box on the right side represents the problem investigated, the box on the left shows the

[339] See van Aken et al., 2007
[340] See van Aken et al., 2007, p. 21
[341] See van Aken et al., 2007, p. 21

"set of theoretical perspectives that are required to study the problem".[342] The box on the bottom depicts the objectives of the research, which are the expression of the research sub-questions included within the main research question: 1) the identification of platform planning and design characteristics of rolling stock; 2) the development of a systematic planning and design methodology for rolling stock platforms.

4.2. Research design: a multiple case study within rolling stock platform projects

The development of modular platform solutions for rolling stock can be considered as a new subject of study in the research field of product platform and modularisation, as this topic has become very popular in the rail industry. However, the stated problem is unstructured and not well understood by BT.[343] According to the problem's characteristics, an exploratory study finalised to theory-building research design seems to provide an appropriate framework for the research.[344]

A case study research is applied if "why" and "how" questions are concerned[345] that is exactly the case of the central research question. It is suitable, in particular, for a phenomenon that needs to be analysed in depth and cannot be isolated from its context.[346] Since developing a platform is a process that involves different actors and highly depends on the context in which it is deployed, it can be hardly controlled and investigated through experiment or history research. The fact that phenomenon and context are not easily separated provides an additional argument to use a case study, according to Yin.[347]

The main interest of this thesis is to investigate the platform development process including planning and design methodologies within BT. Hence, the units of analysis are both the previous platform development projects and the new platform developments led by the CTO (see Figure 23). The platform projects were selected by the author as units of analysis because result to be the only platform-based projects within BT multi-project portfolio. A deep analysis and investigation of BT multi-project portfolio driven by the CTO identified *Bi-level*, *TRAXX*, *Flexity 2* and *Aventra* projects as platforms serving multiple markets segments and customer projects. The platform development projects selected have been identified by the author thanks to preliminary talks with product managers and engineers involved in the projects but overall thanks to author's participation in the investigation of BT multi-project portfolio. In addition, CTO-led platform development was included as unit of analysis because from year 2014 all the platform-based project will be led by CTO. Hence, the sample used for the analysis consists of five cases: four

[342] van Aken et al., 2007, p. 52
[343] See Eisenhardt, 1989, pp. 548-549; Babbie, 2010, p. 91
[344] See Eisenhardt, 1989, pp. 548-549; Blumberg et al., 2011, pp. 254-256
[345] See Yin, 2009, p. 13
[346] See Yin, 2009, p. 13
[347] See Yin, 2009, p. 13

previous platform development projects and the new platform development led by the CTO (see Figure 23).

Finally, as stated in 3.3, the selection of the cases was driven by the rationale to consider only the cases that "are particularly suitable for illuminating and extending relationships and logic among constructs".[348]

For the problem set forth in this study, a multiple case study design offers the opportunity to explore in depth the characteristics of different platform development projects. This would not be possible through the investigation of BT as a single case study mainly because the platform development projects are completely independent from each other. Thus, rather than considering BT as one exemplar case, multiple cases within BT are investigated, in order to reveal both commonality and critical differences.[349]

The selected approach increases the robustness and reliability of the results, given that it facilitates the collection of consistent data.[350] However, since all platform projects were developed within BT, the approach does not improve the low external validity of the study (Saunders et al., 2009, p. 8).

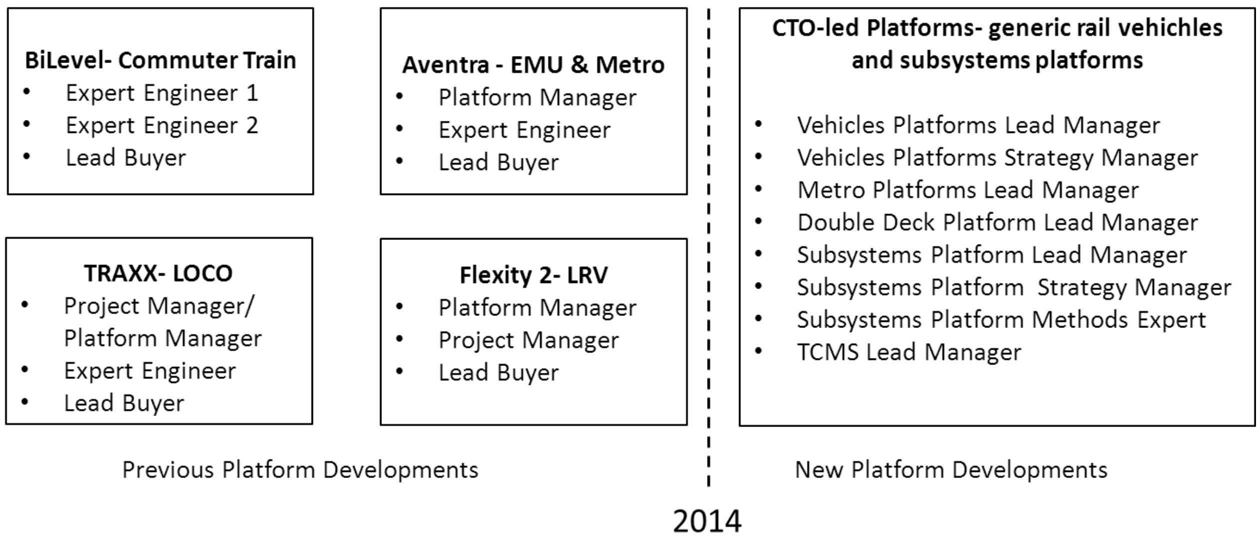


Figure 23: Case studies and interview participants (based on own elaboration)

The findings of the case studies are presented in two complementary forms consisting of the "within the case study" and the "cross-case analysis". This distinction is needed in order to

[348] See Eisenhardt & Graebner, 2007, p. 27
[349] See Baxter & Jack, 2008, p. 550
[350] See Saunders et al., 2009, p. 7

become familiar with each isolated case as well as to compare and generalise results across cases.[351]

4.3. Data collection: gathering qualitative data through semi-structured interviews

According to King the goals of a qualitative research interview is to obtain the view of the interviewee and to understand how he has come to this perspective.[352] This approach also enables the author to ask for further elaboration of the most relevant parts. Thus, data collection does not rely on quantitative surveys or structured interviews, but on semi-structured interviews.

Interviews are held with professionals that participated directly and actively in the platform development project. For the CTO-led platforms the author sought to identify and interview the key people responsible for platform development in CTO. They are mainly middle and top managers with a background in engineering and experience in product development. The identification of the participants was supported by the Platform Management Office of the CTO that provided to the authors the contacts of platform managers of the selected projects. During the first contact with the platform managers the authors asked them to provide two other contact persons, one appointed to platform engineering and another to platform procurement. Hence, except for *Bi-level* platform and CTO-led platforms, a platform manager, an expert engineer and a lead buyer were interviewed.

For the *BiLevel* platform only expert engineers were identified. However, their high degree of experience in product development guaranteed robustness and consistency of the results. By contrast, for CTO-led platforms the lead buyer could not been identified because nobody was appointed yet.

The semi-structured interviews were done face-to-face or via phone; each interview lasted between 75 minutes to 90 minutes and, to increase validity in data collection[353] all the interviews were recorded with the permission of the participants.

A total of 20 interviews were conducted and when needed a series of follow-up emails or face-to-face talks helped the author to clarify doubts or to deepen specific information.[354] The interview protocol started with an introduction of the research project in order to establish a common understanding of the topic and increase content validity[355]. The interview design is flexible and does not include only questions derived from the theory but also further insights identified by the author *in itinere*. In order to facilitate the flow of the interview and the collection of relevant

[351] See Eisenhardt, 1989, p. 540
[352] See King, 2004, p. 50
[353] See Quinlan, 2011, p. 305
[354] See Babbie, 2010, p. 31
[355] See Babbie, 2010, p. 153

results, common guidelines and directions steered the interviews. Two separate interview guideline streams were created. While common interview guidelines were used for platform managers and expert engineers (see Annexure 4), a different interview guideline was designed for lead buyers (see Annexure 5).

The decision to use the same interview guidelines for both platform managers and expert engineers was motivated by the purpose of collecting a technical and commercial perspective on the same topic.

To ensure construct validity[356] the author asked to each participant to provide additional documents mainly consisting of BT process descriptions, platform methodology descriptions and illustrative platform presentations. When possible, excel files used during the planning and design methodologies were also provided. Furthermore, the researcher was a participant observer in the big CTO action “Inventory Taking” where he could gather indispensable contributions regarding the different platform development projects. Working actively within the CTO helps the author understand in-depth the dynamics regarding the new platform development project. These activities in combination with the transcript of the interviews and the BT documents allowed data triangulation and formed the case study database.[357]

Finally, the entire qualitative data obtained was analysed following the approach suggested by Quinlan.[358]

The analytical process can be summarised in the following steps:

1) Read and listen to the empirical evidence, consisting of the entire data collection

2) Listen to the themes identified within the empirical evidence until saturation is reached

3) Report the major themes identified with the corresponding findings within the cross-case analysis

In the presentation of the findings, the concepts highlighted during the interviews were quoted in both “within the case study” and “cross-case analysis”. To increase the reliability of this research, also the key points of the interviews are provided in the appendix section (see Annexure 2 and 3).

[356] See Yin, 2009, p. 41
[357] See Yin, 2009, p. 41
[358] See Quinlan, 2013. p. 305

5. Modular platform development in practice in rolling stock divisions

5.1. Within case analysis: grasping different platform developments in BT

5.1.1. *BiLevel* platform: the adaptation of an existing product to cover a multiple array of customer requirements

The *BiLevel* platform forms the baseline for commuter trains that operate under the North American standards. It was of the earliest attempts of BT to develop a platform and was originally designed as a single product (see Annexure 10). Only in a second stage and "by accident", the product became a platform. In fact, the demand of multiple customers for the same product characteristics led BT to modify and adapt the product architecture of the existing product to new customer specifications. Although the *BiLevel* platform was a result of a "customer-driven" (bottom-up approach), it generated faster time-to-market- i.e. three times faster than the previous deliveries- and less overall risk due to the maturity of the product.

Aspects of complexity

Fairly universal for different types of rolling stock, their main characteristic consists of the diversity and the variety of the requirement specifications across regions and countries in which trains operate. Rail vehicles operate under different standards that often vary from one country to another. Thus, commonality across products is lower than in other industries such as the automotive or aerospace industry. According to one expert engineer, the rolling stock industry is the most difficult environment to develop a platform. However, since the rail gauges in the USA were standardised 25 years ago, in the *BiLevel* specific case the alignment of the platform to different rail infrastructures was not as difficult as it could have been for a metro product that mostly operates on different infrastructures.

Platform development characteristics

"To cope with these challenges" one of the expert engineers claims it is important to understand and analyse the environment in which the product operates. In doing so, paramount activities consist of deciding how to standardise basic configurations from a wide array of market requirements and how to enable modularisation within the platform. In *BiLevel* a key enabler of modularisation was the standardisation of the most critical interface specifications- i.e. keeping the size of the exterior doors changeable but standardising the door control system.

Processes and methods

As mentioned before the development of *BiLevel* followed a bottom-up approach because the platform was the result of a successful product adapted to be reused in other customer projects. In the redesign phase, "design to cost" steered the entire *BiLevel* product development.

Interface control documents were created to facilitate *BiLevel* adaptation. An interface document consists of a matrix-based layout for each subsystem, where the mechanical, electrical and software component interfaces are specified and listed.

<u>Design Network</u>

A platform development process should also involve key suppliers at an early stage in the development process in order to better understand the directions of the markets and integrate technical capabilities that BT lacks. For strategic subsystems, a platform project should involve suppliers in the development activity already before the "notice to proceed". However, according to the lead buyer this was not possible for *BiLevel* because of their particular bottom-up approach as explained before. For *BiLevel* mainly the white box and less frequently the black box approach were applied. For example, they HVAC systems relied on in-house knowledge and capabilities where BT defined the interface specifications and outsourced the realisation to the supplier. The suppliers selected to develop the *Bilevel* platform guaranteed cheaper manufacturing, fast development time as well as they assumed a consulting role in the design phase whenever the white box approach was applied. In the development of *BiLevel* platform the interface control document was the main way of cooperating with the suppliers. The document shows all the defined interface specifications of the platform. Their definition was indispensable to enable black box engineering. However, the platform project lacked a pre-defined process to define not only the interface specification with suppliers but also the overall collaboration in the platform development. Furthermore, BT's influence on suppliers was not so strong and very often the supplier was not keen on change its standardisation strategy and use BT's interfaces.

5.1.2. *TRAXX* platform: a long-lasting reuse of functionality across product families and platform generations of locomotives

TRAXX locomotives feature a great number of identical elements, e.g. vehicle dimensions, machine room concept, brake equipment, bogies, traction motors and drive systems, signalling and communication systems, control and diagnostic systems, as well as driver's cab (see Annexure 11).[359] The first TRAXX was developed ten years ago and it evolved over the years. The principles that guide all the platform generations and platform segments - in locomotives called also corridors- are the reuse of functionality and the replacement of obsolete subsystems, facilitated through the use of modular configurations. One product platform consists of several product families. Each product family covers a predefined corridor and it is formed by the core

[359] BT-Doc, 2013

part and several elaborated & engineered packages that ensure its customisation. The target of the LOC is to develop platforms only outside of the customer project - off-cycle predevelopment. Such an achievement will lead BT to faster product development cycle, higher cost saving and more room for innovation.

Aspects of complexity

According to the interviewee, two aspects are the main causes for complexity in locomotive: the diversity of the homologation process across countries and the many interface specifications within the product. Modularity can facilitate the designing activities for different standards and norms as well as reduce the coupling across interface specifications - i.e. enabling module substitution. The diversity of environmental interfaces also forms a big constraint for reuse.

Platform development characteristics

The key platform characteristic is flexibility. It allows platforms to cover both the entire set of different requirements and their future evolutions. Due to the high diversity of market requirements and norms and standards, the expert engineer suggests to focus on sets of solutions instead of attempting to standardise the vehicle as one big block. However, it is also important to have a complete picture of the platform architecture in order to identify and manage changes at different hierarchical architecture levels. To limit risk of high component sensibility, a loose coupling of the module interfaces and standardisation of the external interface are needed.

Processes and methods

The methodology adopted for planning and designing the *TRAXX* platform is based on a detailed functional analysis supported by specific tools available in BT. The process consists of three steps: 1) gather the requirements from the market through the use of clustering in order to find commonalities, 2) allocate the requirements into basic and optional functions; 3) organise functions through a software-based optimisation method. An interface control document regulates the collaboration with subsystem suppliers. Complementary methodologies are, for example, sensitivity analysis that simulates the effects of changes to those components that show high sensibility to internal specification changes.

Design Network

Since the first *TRAXX* platform development collaboration with the suppliers has increased but according to the expert engineer there is still room for improvement. In fact suppliers should be also considered as the main source of new technologies and innovation in the new platform developments. In the different evolutions of the *TRAXX* platform all the three approaches of supplier-buyer relationships were adopted. Only strategic suppliers, however, were involved in the early process through regular meetings and workgroups based on the Joint Design and Development Process (JDDP) (see Annexure 6). Collaboration was possible by the commitment of both BT and the suppliers to specific performance targets but overall by a fair and trusty cooperation. For the standard components and those subsystems in which BT has long design experience and key capabilities a white box approach was preferred instead of the other two approaches. In presence of non-strategic subsystems, long-term BT-supplier collaboration, trust and power to influence supplier interfaces and make them using our throughout the platform lifecycle, a black-box approach was applied. In the development of *TRAXX* preferred suppliers were involved through the JDDP in order to define the component interface together, however, according to the interviewee sometimes is also useful to gain a strong position against suppliers to influence them to adapt BT interfaces.

5.1.3. *Flexity2* platform: a long list of option module solutions integrated to the platform ensures product customisation and variety management

Flexity2`s unique design concept - creative customisation based on standardised and exchangeable components- allows customers in different countries or urban environments to choose a distinctive look that reflects their specific needs (see Annexure 12).[360] Since the platform was designed to be adaptable to different environments, it is formed by basic modules and a long list of option modules - i.e. between 80 and 90 option modules- that guarantee product customisation across different projects. The principle of physical modularity enables the customisation of many areas of the vehicle, in particular exterior design. For instance, the combination of different modules may model the driver’s cab and shape the entire aspect of the product. The reuse of a list of pre-developed options allows platform-based projects to save a huge amount of engineering hours and achieve economies of scales at component level.

Aspects of complexity

From one project to another the aspects of complexity for LRV are multiple. Trams are products that differ from one city to another and if the components and the architectures used are not managed properly, variety can lead to serious problems. Furthermore, the different authorisation procedures also play a critical role in the development of different products that derive from the same platform.

[360] See BT-Doc, 2009

Platform development characteristics

The solution adopted during the development of *Flexity2* consisted of creating a platform architecture that could support different product variants without increasing risk and cost. Thus, it was decided to apply physical principles of modularity in order to allow the exchange of pre-developed and pre-tested parts. To facilitate the work of engineers and take advantage of their expertise, the platform team decided to redesign and optimise existing solutions. Reducing interface coupling and standardising interface specifications requested high engineering efforts during the development of the platform. However, in the derivative customer projects such a big effort paid back, resulting in high product differentiation with limited efforts- e.g. setting size parameters for the ceiling but allowing different interior design.

Processes and methods

The project manager remarked that the planning phase and the creation of a business case were central activities in the development of *Flexity2*.

The first task consisted of segmenting the markets according to the collected market requirements and standards and dividing them into mature markets, new markets and future markets. In this task, a benchmarking analysis across the competitors helps also the development team to leverage the scope of the platform. This phase initiates the second task consisting of cost targeting analysis aimed at reducing the material cost of the components selected according to the requirements. The bill of material (BOM) of each component was taken from two previous projects that were used as a benchmark. The aim of the method is to redesign the components to reduce their material cost (design to cost). Once the target costs were set, for each subsystem different working group were created. This third task consists of developing the vehicle architecture through engineering workgroups, working in concurrent engineering. Expert engineers and buyers were committed to target costs and to use standardised interfaces in order enable collaboration across teams. At this point, for those components that were more sensible to change in customer specifications, multiple options were created and listed in the product breakdown structure as option modules.

Design Network

According to the lead buyer, suppliers own the technical capabilities to develop the specific components. Therefore their contributions and optimisation proposals are essential in the selection of the most suitable solutions. For the lead buyer the white box approach represents the traditional approach of supplier-buyer collaboration in the railway industry and it is not compatible to a platform development project. By contrast, the ideal approach is the grey box supplier-buyer relationship.

The "frozen core" of *Flexity2* platform and some of the option modules relied on strategic suppliers that were identified after the big effort of reducing the supply base by 50 percent.

To avoid any risk of reliance at least two suppliers per critical component were identified. In case of problems with the preferred supplier, the second supplier was contacted and committed to use the same interfaces. The black box approach was seldom used because was difficult and risky to outsource the entire design and development of a subsystem.

BT should strengthen partnerships with strategic suppliers and spending more time in selecting reliable suppliers since so far it has been not that good in doing both. Generally, BT procurement was used to "do shopping" with suppliers by focusing only on price. The big mistake to change often suppliers often impeded to increase BT learning curve and reuse of the same interfaces.

5.1.4. Aventra platform: BT state-of-the-art platform, serving four different product segments but limited to the UK market

The *Aventra* platform is a new commuter platform for the UK market which provides a basis for a number of projects covering a variety of applications. These applications are designated by four platform segments that are defined as metro, high-speed, medium speed and low speed (see Annexure 13). In addition to the segments defined, various options can be applied to the platform. Examples of options include flexibility of the interiors and the future inclusion of traction batteries. The platform concept and critical requirements are defined in the Aventra platform technical report that is available for each subsystem of the platform. This is a key document for product designers because it shows how requirements vary between segments, and it also defines where provision should be made in the design to accommodate options.[361] The main benefits reached in *Aventra* platform-based derivative projects consist of a reduction of the delivery risk and of the overall costs through the use of a robust platform design.

Aspects of product complexity

A platform can simplify the life of engineers but its development in the rolling stock industry requests several efforts that, according to both interviewees, are mainly due to the large number of component interfaces and to different standards, regulations and market requirements. However, it worth noticing that *Aventra* is a platform conceived for the UK market where the requirements are more predictable than in other countries, according to the platform manager.

[361] See BT-Doc, 2012

Platform development characteristics

According to the platform manager and the expert engineer the organisation of the platform development activities are an important investment for the platform success. The *Aventra* platform team is also quite advanced in platform thinking, including in the definition of platform terminology and processes. *Aventra* embeds robust and high level design concepts that constitute the boundaries of the derivative platform-based projects. The *Aventra* platform enables designers to exchange different option solutions in order to cover the entire product segmentation of the platform – e.g. at subsystem level replacing the HVAC without too much effort. The documentation of the platform consists of specific design rules to which every derivative project is committed. In the limit of its exclusive application to the UK market, The *Aventra* platform allows high customisation whilst offering a common baseline for different product segments, thanks to the combination of basic and option modules. It is worth mentioning that the modules are mainly understood as functional entities and not only as mechanical building blocks.

Processes and methods

The platform development process is based on a strong co-located cross-functional working style with a team-based co-operative approach to new product design, where all the functions involved - i.e. expert engineering, sales, procurement, operations- work in parallel. The process starts with the identification of the market opportunities based on market requirements and previous project requirements. Then, the expert engineers relate them to vehicle technical specifications. At this time, the winning points of the platform, also called vectors of differentiation, are identified and transferred into performance targets - i.e. material cost, reliability, energy and mass- to which every workgroup is committed.[362] The groups are divided into four teams: carbody shell team, underframe team, cab team and interiors team.[363] After that, the vehicle function integration team is responsible for the integration of the subsystems into the vehicle. Thus, once the targets are set, the groups can start cooperating under common guidelines in concurrent engineering. Preferred suppliers are also involved through the interface of procurement and thanks to the JDDP process.

Design Network

Since BT buy more than 70% of the components that are integrated in its platforms, there so no possibility to exclude suppliers from a platform. The main component suppliers were involved in

[362] See BT-Doc, 2012
[363] See BT-Doc, 2012

long-term relationship to achieve economies of scale and scope. For the lead buyer, the white box approach was not an option to consider for a platform project, since it is more efficient to develop the subsystem together with supplier or outsource it completely. Different reason and condition lead *Aventra* team to choose the grey box or the black box approach. A grey box approach was preferred when co-location could be achievable and willingness to collaborate and share key information that is exclusive knowledge of the supplier existed. The JDDP enabled us to involve suppliers in a grey box collaboration. *Aventra* team managed to have regular meetings with key suppliers since they were part of the concurrent engineering workgroups. By contrast the black box approach was preferred when the component interfaces could be well defined upfront and the supplier was willing to them as well as when the supplier showed to be capable to be autonomous in providing a good and reliable solution. However, in *Aventra* it was always an iterative process and not a complete black box approach since a regular reciprocal feedback was needed. A key factor in managing collaboration with suppliers in platform development is aligning component interfaces upfront because generally BT does not have enough power to influence and force the suppliers to use BT interfaces. In the development activities, two/or three suppliers were committed to the concept design of one subsystem. At least two suppliers per subsystem joined the platform development team, but then in the customer project only one was selected. This approach limits the risk of reliance on only one supplier.

5.1.5. CTO-led platforms: flexible, robust and modular platforms for multiple performance and product segments

The new CTO leads and guides the "O*ne*BT" way of how the company plans, differentiates and engineers the future of BT product and service offerings. "*OneBT*" actions aim at reducing risk, cost and time-to-market, no-recurring cost and at entering new markets. The strategy of CTO is twofold. In the long-term, it consists of developing modular vehicle platforms and standardising systems and processes as a basis for competitive products. CTO started already the planning activities of the first platform that will steer the other product segments. This will enable faster project execution based on predefined modules, architectures and best solutions. On the short-term the strategy is based on making available preferred existing solutions for global re-use to improve execution and to reduce engineering costs and technical risks in upcoming projects. This will also be the first step towards the creation of a library of BOM solutions, proved processes and methods as well as the establishment of different communities of engineering experts. To make this scenario happen, cross platform synergies need to be empowered. This is essential because it will enable the different platforms to align on architectural and functional specification requirements. Having a common understanding of the complexity of BT products and working together to find effective solutions that will steer the direction of the platform development are crucial factors for the success of BT´s platform strategy.

Aspects of product complexity:

During the interviews, the participants identified multiple aspects of complexity that are strongly associated with rolling stock. Starting from internal product complexity, it is worth to mention that rolling stock are highly hierarchical systems formed by “systems of systems” and, thus, developed in a very complex design. The complexity of rolling stock design is also the result of the combination of electrical circuits, mechanical parts and software at different levels of the product architecture. In addition aerodynamic, weight and thermal principles are important concepts that guide rolling stock engineers but often complicate their design activities. Due to these internal aspects, the development of rolling stock necessitates the coordination of different knowledge inputs from several disciplines such as physics, electronics, mechanics and informatics. This complex picture reflects the complexity of the environment where rolling stock are produced and operate. Different market requirements mainly in terms of standards, norms and diverse infrastructures request in-depth analyses of the various realities, according to the interviewees. Different regulations require different shapes and sizes, fire protection and crash norms that make it difficult to sell the same product worldwide. The diversity of climatic and operating conditions in various regions of the world, the project-driven activities finalised to the development of a unique product and the relative low production volume limit reuse across projects and inhibit learning effects and economies of scale within the company.

Platform development characteristics

Although different actors in CTO provided multiple definitions and platform development characteristics, the author sought to collect those concepts and solutions that are commonly shared across the interviews. Firstly, it is clear that CTO-led platforms are not perceived as complete vehicles but as sets of architectures, integrating components and subsystems through standardised interfaces that enable scalability and exchangeability of design and technical solutions. Second, to permit scalability and exchangeability of solutions, platforms should embed a high degree of modularity, in particular for those areas of the system that are subject to changes and variations across different product families and customer products. The key point in platform development is to keep platform configuration “flexible but stable” at the same time through designing activities aimed at generating robust and adaptable solutions. Flexibility and robustness are undoubtedly two important platform characteristics. However, a platform should also be designed to the extent that it can reduce material, design, manufacturing, assembly and lifecycle cost. Being cost-efficient may enable also BT to access new markets and produce relatively low-cost products for emerging and developing countries.

Processes and methods:

Since CTO started its new mandate in the new *"OneBT"* organisation in January 2014, a platform development process is still missing. However, during the interviews, the author collected many inputs and suggestions for the ideal platform development led by CTO. Different perspectives and priorities seem to converge towards the same direction. It is clear that CTO should follow a top-down approach in collecting and prioritising market requirements as well as transferring them into technical specifications. The Subsystems platform expert pointed out how effective the QFD method is in performing these activities. However, the method is still not applied and used within the CTO. According to the majority of the interviewees, before "reinventing the wheel" and developing new design concepts, it is opportune to screen the existing solutions of BT´s product portfolio and identify potentials for reuse. The "Inventory taking", a cross-divisional action of CTO guided by Vehicles Platforms, aims at collecting the available knowledge about proven, working BT solutions and create a first reuse portfolio through a library of solutions (see Annexure 7). To achieve this result Subsystems Platforms is working at the implementation of a tool-based library called TCUA (see Annexure 8). TCUA has the objective to simplify the work of engineers and enable them to reuse what has been developed in the past. Finally, for the first time the company applied the DSM methodology in analysing the component specifications of their systems. Although the method is in the early phase of its deployment, many expert engineers could already apply it during a pilot promoted by Subsystems Platform (Annexure 9).

Design Network

The CTO-led platform development has not yet defined BT-supplier collaboration interfaces and a common approach to involve suppliers in platform development except for the JDDP process.

5.2. Cross-case analysis: understanding platform planning and design characteristics in rolling stock

Analysing and comparing the above case studies led to the identification of a number of issues related to platform development characteristics, process and methods.

5.2.1. Platform planning: capturing standards and market requirements, analysing existing solutions and achieving cost efficiency

The interviewees of all platform projects recognised the importance of carefully analysing standards and market requirements by pointing out that in the railway industry market requirements collection and clustering result in a greater effort if compared with other industries. This is mainly due to the diversity and complexity of homologation and authorisation processes regulated by different national authorities [364], the heterogeneity of rail infrastructures worldwide[365]and the specificity of customer requirements in terms of performances, operating conditions, industrial design and environmental conditions.[366]

This activity may be easier when platform-based products operate under the same standards as it is the case of *Aventra* and *BiLevel*, both developed exclusively for the UK and USA markets[367]. However, it may become more complex when platform-based products are designed to operate in different countries as *TRAXX* locomotives and the CTO-led platforms.[368] According to the project manager of *Flexity2* understanding in-depth the market requirements prevents companies to incur in cascading changes during the redesign activities.[369] Despite the importance of such planning activity in the railway industry, all of platform-based projects lacked a systematic process for capturing the key market requirements and identifying those that are likely to change across the product families and the derivative products.

A second platform development characteristic of rolling stock consists of developing the new platform by taking into account old existing products that have reuse potential. The head of CTO Vehicles Strategy stressed the importance of screening the existing product portfolio in order to identify components, subsystems or integration and assembling methods that can be easily adapted and reused in the new platform.[370]

[364] See BiLevel (1); TRAXX (2); Flexity 2 (2); CTO (2,3,6,7)
[365] See TRAXX (1); Flexity 2 (2); CTO (2,3,4,5, 6, 8)
[366] See BiLevel (2); Flexity 2 (1); Aventra (1); CTO (1,3,8)
[367] See BiLevel (1,2); Aventra (2)
[368] See TRAXX (2); CTO (2,3,7)
[369] See Flexity (2)
[370] See CTO (5)

Only the CTO-led platform development undertook such a global action called “Inventory taking” aimed at screening the product portfolio and identifying those components, methods and processes that will form the platform library of solutions (supported by TCUA software). Contrary to the CTO-led platforms, the other platform developments limited the reuse of existing technical solutions to those that were previously developed within the same division or site. According to the analysis of the cases, the “Inventory taking” and the TCUA software are the only actions towards the creation of a unique source of common solutions. [371]

All the interviews report that the development of a new platform is very time and resource consuming. Thus, due such constraints platform development in BT mainly focuses on achieving platform cost efficiency. [372] Furthermore, the high price sensibility of the rolling stock tendering process as well as the appealing opportunity of accessing emerging markets with platform-based products[373]make the evaluation of the platform cost indispensable already in the beginning of the platform development process.

An additional platform development characteristic mainly implemented by *Aventra* and *TRAXX* is the strategic collaboration with key suppliers. It consists of establishing strategic partnerships with preferred suppliers in order collaborate with them on the platform development.

Since suppliers own specific capabilities and have an in-depth knowledge of the components they develop BT cannot not only negotiate better material and development costs but can also take advantage of specific supplier knowledge and capabilities.

5.2.2. Platform design: defining architectures and interfaces to ensure flexibility, robustness and collaboration

All platform development projects lacked a systematic platform design process since most of them apply single product design technics adapted to platform design. A common key characteristic of rolling stock platform consists of achieving a balance between platform robustness and platform flexibility. However, the various platforms analysed in this research show different aspects of architecture flexibility.

For instance, *Flexity2* shows high mechanical flexibility but is limited to physical reuse within LRV;[374] whereas *Aventra* shows a high flexibility across different product segments but limited to the UK market.[375]

[371] See CTO (4,5)
[372] See BiLevel (2); TRAXX (1); Flexity 2 (1,2); CTO (2,4)
[373] See BiLevel (2); CTO (4)
[374] See Flexity 2 (1,2)
[375] See Aventra (2)

A similar evaluation can be done for the high functional flexibility of *TRAXX* across different corridors but limited to LOC segments;[376] or for *BiLevel* reuse that is feasible only under the North American standards.[377]

By contrast the flexibility of the CTO-led platforms is planned to be higher in terms of mechanical and functional reuse as well as because CTO-led platforms aim at serving different product segments and markets. [378]

Finally, during the interviews a consensus concerning the importance of interface strategies in platform development was achieved.[379]Every interviewee recognised the necessity of predefining and standardising the most critical interfaces within the platform architecture in order to enable and facilitate collaboration in network design.

5.2.3. Design Network: Design Network: Design Network: grey box and black box buyer-supplier relationships as main approaches of supplier involvement in platform development

All the four platform projects recognised the importance of involving suppliers in platform development. In BT component suppliers have a crucial role in the development activity. In fact, the rail rolling stock manufactures at BT is characterised by the purchase of almost 70 percent of components integrated in the vehicle[380]. The contribution of suppliers is very important because they are often able to produce component at lower cost and faster time-to-market thanks to their specialised experience. Thus, most of the times they own specific technical capabilities that BT lacks.[381] In a platform development supplier contribution is even stronger than a single-product development project since they can push the introduction of modular innovations[382] within the platform and support BT to better understand the evolution of the market and the future market demand.[383] In fact, supplier suggestions and proposals are unavoidable to select the best platform solutions in their specific domain.

In chapter 2.4.3 three different supplier-buyer relationships were identified, however, the grey box and black box approach result to be the most applied in platform development.[384]

[376] See TRAXX (1,2)
[377] See BiLevel (1)
[378] See CTO (1,4,5,6,7,8)
[379] See BiLevel (1,2); TRAXX (1,2); Flexity 2 (1); Aventra (2); CTO (1,3,4,5,6,7)
[380] See Aventra, (3)
[381] See BiLevel (3), Flexity2 (3)
[382] See TRAXX (3)
[383] See BiLevel (3)
[384] See BiLevel (3), TRAXX (3), Flexity2 (3), Aventra (3)

The white box approach is seen as the traditional way of dealing with suppliers at BT and does not have a wide application in platform projects.[385] It is only used for the components in which BT has developed and owns great know-how as well as for simple and less risky components.[386] For example in *BiLevel* platform the HVAC system mostly relies on in-house knowledge and capabilities but development and manufacture are outsourced to the supplier.[387]

The grey box and the black box approach are commonly applied in the four platform projects. The decision of the type of supplier involvement depends on the capabilities owned by both BT and the supplier, the strategic importance of the component and the development risk.[388] A grey box approach is preferred when the supplier owns the supportive knowledge that is needed to develop the system. For the lead buyer of *BiLevel*, it consists of a better understanding of the market for the specific subsystem and awareness of all the development risks.[389] In *TRAXX*, *Flexity2* and *Aventra* the grey box approach was applied only for the main subsystems that belonged to the core part of the platform. For this kind of approach a long-term collaboration agreement was established and the selected suppliers were involved very early in the development process though the JDDP process.[390] This approach is often used when BT wants to leverage strategic know-how from the supplier.[391] However, it requests early supplier involvement, co-location, mutual trust and knowledge of the partner and open exchange of information.[392] The black box approach is widely used for those subsystems that are not strategically important for BT and need specialised design capabilities to be developed.[393] In this case it is important to define up-front the interface specifications and the performance goals of the subsystems whilst leaving complete freedom to the supplier for the design and development.[394] However, since it is very difficult to influence suppliers in using BT interfaces, according to the four lead buyers it is convenient to define the interfaces together and standardise them across the various derivative platform-based projects.[395]

Not only the black box approach but every type of involvement in platform development needs the up-front definition and standardisation of interface specifications.[396] When BT has not enough power on influencing the suppliers, it is useful to define the interface together with at least two suppliers and apply the JDDP. The JDDP process is a general approach to enable design and

[385] See Flexity2 (3), Aventra (3)
[386] See BiLevel (3), Aventra (3)
[387] See BiLevel (3), TRAXX (3)
[388] BiLevel (3), TRAXX (3), Flexity2 (3), Aventra (3)
[389] See BiLevel (3)
[390] See TRAXX (3), Flexity2 (3), Aventra (3)
[391] See BiLevel (3)
[392] BiLevel (3), TRAXX (3), Flexity2 (3), Aventra (3)
[393] See BiLevel (3), TRAXX (3)
[394] See TRAXX (3)
[395] BiLevel (3), TRAXX (3), Flexity2 (3), Aventra (3)
[396] Flexity 2 (3), Aventra (3)

development with supplier but it does not consist of a complete approach of supplier involvement. Furthermore, it does not distinguish in the process description and application between the grey box and black box approach.[397]

In *TRAXX*, *Flexity2* and *Aventra* the main way of supplier involvement was based on long-term agreement with preferred suppliers, generally two, that are involved in the platform development through JDDP.[398] While the main component design characteristics and interfaces are shared by the two suppliers, for each project only one supplier is selected. According to the lead buyers of *TRAXX* since in the railway industry is very difficult to switch from one supplier to another, it is crucial to establish long-term agreements with at least two suppliers in order to limit high dependency on one supplier and risk of reliance.[399] However, trust and successful previous relationship with the supplier are always needed to establish a strategic partnership in platform development.[400]

[397] BiLevel (3), TRAXX (3), Flexity2 (3), Aventra (3)
[398] TRAXX (3), Flexity2 (3), Aventra (3)
[399] See TRAXX (3)
[400] TRAXX (3), Flexity2 (3), Aventra (3)

5.3. Confronting literature and empirical findings from the case studies

Theoretical insights are confronted to the empirical findings of the case studies to verify platform planning and design characteristics of rolling stock and eventually identify additional characteristics and methods (see Table 7).

CoPS platform planning and design characteristics	Source from:	Rolling stock platform planning and design characteristics	Case studies: *BiLevel*	*TRAXX*	*Flexity 2*	*Aventra*	CTO-led platforms
2.4.1- Ensuring platform variety to meet differences and changes in customer requirements, cost reduction and standards	literature	A) Analyse market, standard and cost requirements	Indicated	Indicated	Indicated	Indicated	Indicated
	literature	B) Segment the market	Not indicated	Indicated	Indicated	Ambiguous	Indicated
	literature	C) Transfer key requirements into technical characteristics	Not indicated	Ambiguous	Ambiguous	Ambiguous	Indicated
	literature	D) Identify variable and stable platform components	Not indicated	Ambiguous	Indicated	Indicated	Indicated
	case studies	E) Analyse the existing product portfolio or library of solutions	Not indicated	Indicated	Indicated	Not indicated	Indicated
2.4.2- Ensuring platform changeability to develop robust, flexible, agile and adaptable platforms	literature	F) Analyse coupling and interface specifications	Not indicated	Indicated	Indicated	Ambiguous	Indicated
	literature	G) Reduce interface coupling and standardise interface specifications	Not indicated	Indicated	Indicated	Ambiguous	Indicated
	literature	H) Identify potential for reuse at different hierarchic layers of the system	Not indicated	Indicated	Not indicated	Not indicated	Ambiguous
	literature	I) Exchange different option solutions with the same architecture	Indicated	Ambiguous	Indicated	Indicated	Indicated
	case studies	K) Focus on set of predefined platform concepts, components and methods	Ambiguous	Indicated	Ambiguous	Indicated	Indicated
2.4.3- Ensuring collaboration in the design network	literature	L) Supplier integration in platform design and development	Indicated	Indicated	Indicated	Indicated	Not indicated
Planning and design methods	literature	Market segmentation Grid (A; B)*	Not indicated	Ambiguous	Not indicated	Not indicated	Ambiguous
	literature	Quality Function Deployment (C)	Not indicated	Not indicated	Not indicated	Not indicated	Indicated
	literature	Generational Variety Index (D)	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated
	literature	Design Structure Matrix(F)	Not indicated	Not indicated	Not indicated	Not indicated	Indicated
	literature	Change Propagation Index (D; F)	Not indicated	Not indicated	Not indicated	Not indicated	Indicated
	literature	Hierarchic Layer Analysis (G; H; K)	Not indicated	Not indicated	Not indicated	Not indicated	Indicated
	case studies	Cost driver analysis or Design to Cost (D)	Not indicated	Indicated	Indicated	Indicated	Indicated
	case studies	Inventory Taking (E)	Ambiguous	Not indicated	Not indicated	Not indicated	Indicated
	case studies	Library of solutions or Team Centre Unified Architecture (E)	Ambiguous	Ambiguous	Not indicated	Not indicated	Indicated
	case studies	Joint Design & Development Process (L)	Indicated	Indicated	Indicated	Indicated	Not indicated

Indicated | Ambiguous | Not indicated

* Letters in brackets refer to respective characteristic

Table 7: Confronting preliminary theoretical findings and empirical insights (own elaboration)

6. Solving the real-life problem: description and application of the platform planning and design methodology for rolling stock

The goal of the case study was to validate the theoretical findings, i.e. to check whether the platform planning and design characteristics and methods identified in the literature can be applied to rolling stock. According to the combination of findings identified in both literature and case studies a platform planning and design methodology can be developed. The following 9-step process describes the planning and design methodology:

A. Define the product segments and the markets covered by the platform
B. Analyse market opportunities and segment the market to define the platform-based product families
C. Identify market & standards requirements and transfer them into engineering metrics and target values
D. Map the engineering metrics to the components and identify the components of that have the higher level of redesign required to meet the different engineering metric target values
E. Analyse cost drivers to identify the components that more impact the cost structure of the platform
F. Identify critical components for platform flexibility by analysing coupling between components
G. Analyse the library of solutions to identify reusable concepts, components and methods
H. Selected and involve preferred suppliers in the JDDP process by defining the type of design collaboration.
I. Select the design concepts to stabilise the critical components and to define which components remain stable and which variable across the product families

The example of a HVAC for rolling stock saloon is used throughout this description. The application and the validation of the method were supported by two HVAC expert engineers that provided continuous guidance and recommendations to the author. Due to the large number of parts only the major components of the saloon HVAC have been considered.

HVAC systems are installed in almost all main line rolling stock (see Figure 24). They are very difficult to standardise since they are mainly adapted to the climatic conditions of the country where the rolling stock operates and to the standard requirements of specific rolling stock segments. Figure 25 shows generic HVAC operating diagram in which the main HVAC components are highlighted.

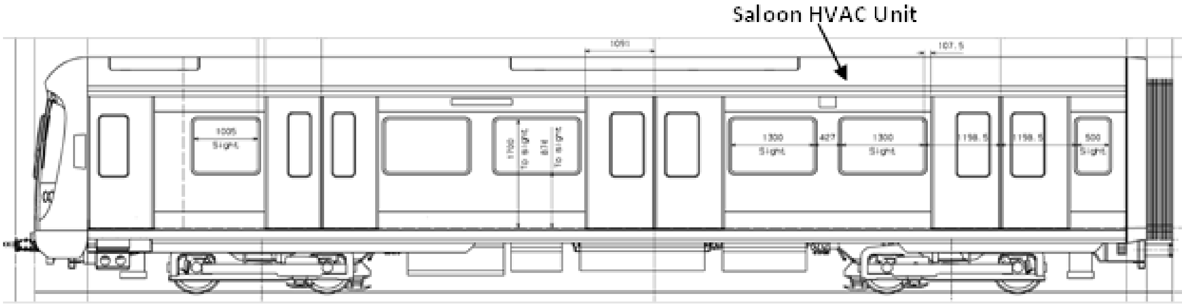


Figure 24: HVAC system integration in a generic rail vehicle (BT drawing)

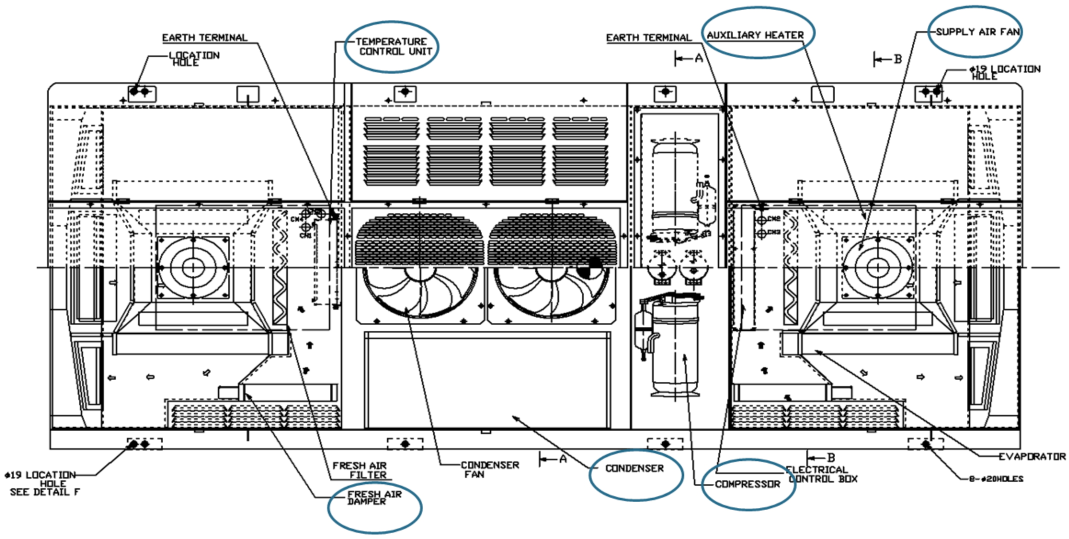


Figure 25: Generic HVAC system diagram with main components highlighted (BT drawing)

A. Define the product segments and the markets covered by the platform

Defining the platform strategy is the first step of the platform development process. It steers the entire process and consists of identifying which product segments and which regional markets are covered by the new platform. This decision is always aligned with the vision and strategy of the company and strongly relies on the opportunities offered by the market. In this example the targeted product segments are the High Speed Trains (HTS) and the Metro vehicles (Metro) (see Figure 26), whereas the targeted market is Europe and part of North Africa (see Figure 27).

One of the characteristics of rolling stock is that they operate under specific standards and norms. Since in the selected market European standards and norms are in force, the EN-15380-2[401], EN-14750-1[402] and EN-13129-1[403] standards are here applied to develop a HVAC for a new platform.

[401] EN-15380-2, 2006
[402] EN-14750-1, 2006
[403] EN-13129-1, 2003

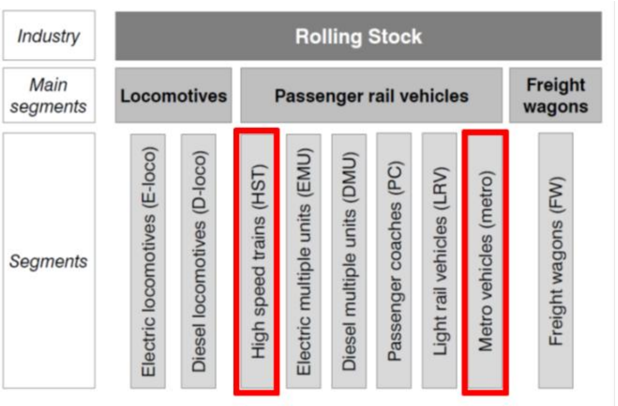


Figure 26: Selection of rolling stock segments covered by the new platform (own elaboration)

Figure 27: Selection of the targeted market covered by the new platform (own elaboration)

B. Analyse market opportunities and segment the market to define the product families based on the platform

The second step consists of analysing market opportunities and identifying potential for a new platform development. Since rolling stock is based on project-driven development, one way of identifying platform and product family potential may consist of looking for key requirements of future projects in the targeted market. Different factors can be selected to cluster the projects and segment the market. For the HVAC example, price segment and climatic zones[404] are used to cluster the projects into different product families. The price segments are differentiated between low cost and high cost, whereas the climatic zones between zone 1 (hot climatic conditions in the summer and temperate climatic conditions in the winter) and zone 2 & 3 (temperate climatic conditions in the summer and cold climatic conditions in the winter).

For each project the respective climatic zone, price segment, product volume and starting date are estimated in order to evaluate whether the project is in or out of the platform scope (see Table 8).

[404] For the climatic zones the EN-14750-1 is applied

Figure 28 shows the first phase of the product and market segmentation. HST and metro projects are plotted on the axes to identify the most suitable platform leverage strategies for the market.

Product	Market	Project start	Price segment	Climatic zone	No. of cars	Scope
HST	UK	01.05.2015	High-cost	Zone 1	160	In scope
Metro	UK	01.10.2018	High-cost	Zone 1	120	Out of scope
HST	Portugal	01.02.2016	Mid-High cost	Zone 1	100	In scope
HST	Spain	01.01.2017	Mid-High cost	Zone 1	160	In scope
Metro	Spain	01.02.2016	Mid-High cost	Zone 1	100	Out of scope
Metro	Spain	01.07.2016	Mid-High cost	Zone 1	80	Out of scope
HST	France	01.04.2015	High-cost	Zone 2	150	In scope
HST	France	01.01.2016	High-cost	Zone 2	180	In scope
HST	Netherlands	01.01.2015	High-cost	Zone 2	120	In scope
HST	Italy	01.11.2016	High-cost	Zone 1	200	In scope
Metro	Austria	01.03.2015	High-cost	Zone 2	180	In scope
HST	Morocco	01.09.2017	Mid-High cost	Zone 1	140	In scope
Metro	Tunisia	01.08.2016	Low-cost	Zone 1	140	Out of scope
Metro	Germany	01.04.2015	High-cost	Zone 2	200	In scope
Metro	Germany	01.05.2015	High-cost	Zone 2	180	In scope
Metro	Germany	01.02.2016	High-cost	Zone 2	220	In scope
HST	Germany	01.05.2018	High-cost	Zone 2	200	In scope
HST	Germany	01.05.2017	High-cost	Zone 2	140	In scope
Metro	Poland	01.05.2017	Low-cost	Zone 3	150	In scope
Metro	Poland	01.10.2017	Low-cost	Zone 3	120	In scope
HST	Norway	01.08.2015	High-cost	Zone 3	100	In scope
Metro	Norway	01.01.2015	High-cost	Zone 3	200	In scope
HST	Sweden	01.10.2018	High-cost	Zone 3	120	In scope
Metro	Sweden	01.04.2016	High-cost	Zone 3	180	In scope
HST	Lithuania	01.08.2016	Mid-High cost	Zone 3	80	In scope
Metro	Latvia	01.01.2018	Low-cost	Zone 3	120	In scope
Metro	Turkey	01.08.2016	Low-cost	Zone 1	160	Out of scope
Metro	Russia	01.03.2018	Low-cost	Zone 3	200	In scope
Metro	Russia	01.06.2018	Low-cost	Zone 3	220	In scope
Metro	Ukraine	01.10.2018	Low-cost	Zone 3	140	In scope

Table 8: Future project opportunities for the targeted segments and markets (own elaboration)

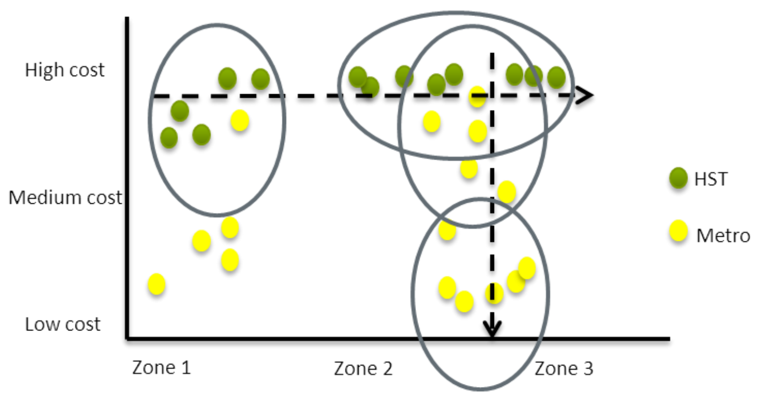


Figure 28: Project opportunities segmentation (own elaboration)

HST projects are only plotted on the top of the axes (high cost) but all of them lay along the three climatic zones. By contrast, metro projects are mainly concentrated on the right side of the axes (zone 3) and span from the top (high-cost) to the bottom (low-cost) of the y-axis. Since the few metro projects on the left side of the quadrant are the only ones that are plotted on zone 1 and since their estimated product volume is relative low they may be considered out of the platform scope. According to the distribution of the projects on the axes, four product families may be based on the new platform development. They are: the "HST Hotline," "HST Coldline," "Metro High-end" and "Metro Low-end" (see Table 9).

Product Family	Product	Market	Project start	Market segment	Climatic zone	No. of cars
HST Hotline	HST	UK	01.05.2015	High-cost	Zone 1	160
	HST	Portugal	01.02.2016	Mid-high cost	Zone 1	100
	HST	Italy	01.11.2016	High-cost	Zone 1	200
	HST	Spain	01.01.2017	Mid-high cost	Zone 1	160
	HST	Morocco	01.09.2017	Mid-high cost	Zone 1	140
HTS Coldline	HST	Netherlands	01.01.2015	High-cost	Zone 2	120
	HST	France	01.04.2015	High-cost	Zone 2	180
	HST	Sweden	01.06.2015	High-cost	Zone 3	120
	HST	Norway	01.08.2015	High-cost	Zone 3	100
	HST	Germany	01.01.2016	High-cost	Zone 2	140
	HST	France	01.01.2016	High-cost	Zone 2	150
	HST	Lithuania	01.08.2016	Mid-high cost	Zone 3	80
	HST	Germany	01.05.2017	High-cost	Zone 2	200
Metro High-end	Metro	Norway	01.01.2015	High-cost	Zone 3	200
	Metro	Austria	01.03.2015	High-cost	Zone 2	180
	Metro	Germany	01.04.2015	High-cost	Zone 2	200
	Metro	Germany	01.05.2015	High-cost	Zone 2	180
	Metro	Germany	01.02.2016	High-cost	Zone 2	220
	Metro	Sweden	01.04.2016	High-cost	Zone 3	180
Metro Low-end	Metro	Poland	01.05.2017	Low-cost	Zone 3	150
	Metro	Poland	01.10.2017	Low-cost	Zone 3	120
	Metro	Latvia	01.01.2018	Low-cost	Zone 3	120
	Metro	Russia	01.03.2018	Low-cost	Zone 3	200
	Metro	Russia	01.06.2018	Low-cost	Zone 3	220
	Metro	Ukraine	01.10.2018	Low-cost	Zone 3	140

Table 9: Clustering of project opportunities in platform-based product families (own elaboration)

The second phase of the segmentation applies the MSG to help marketing and engineering identify and visualise potential platform leveraging strategies for the product families as they are being developed. According to Meyer and Lehnerd, in this case two leverage strategies are selected, the horizontal leveraging strategy for the HST segment and the vertical leveraging for the Metro segment (see Figure 29).

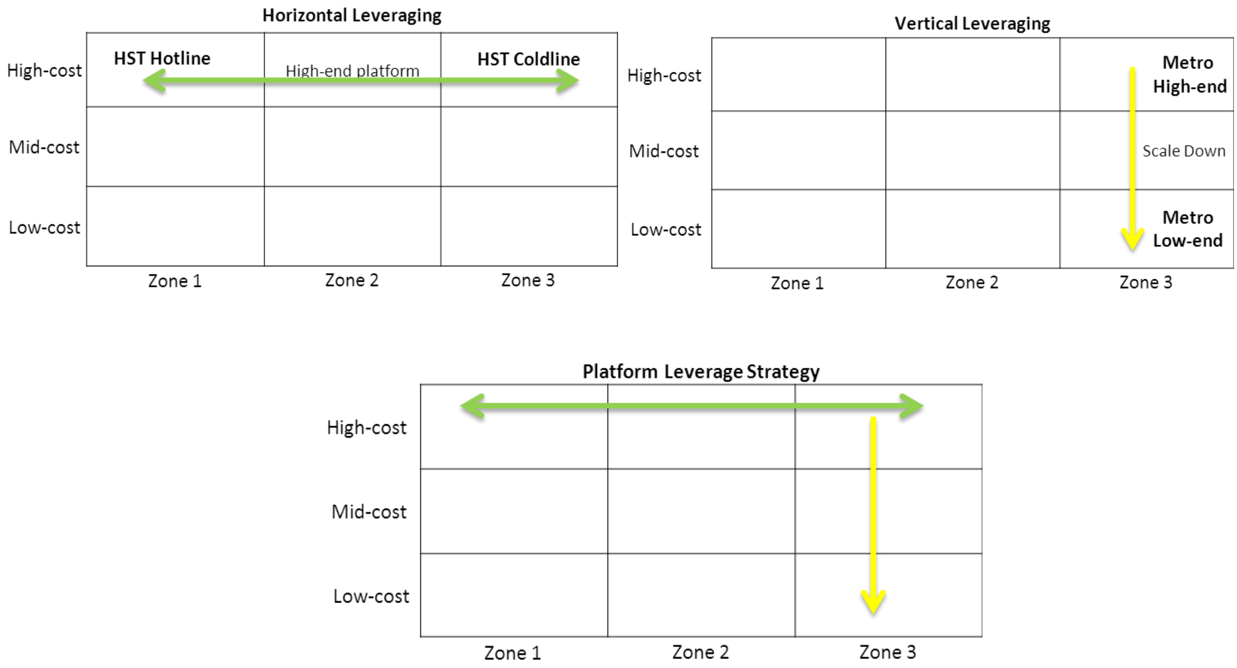


Figure 29: Platform leverage strategy using the MSG (own elaboration)

The platform is first leveraged horizontally going from HST high-end for climatic zone 1 to HST high-end for climatic zone 3. Then, at a later stage it is leveraged vertically spanning from Metro high-end for climatic zone 3 to Metro low-end for climatic zone 3.

C. Identify market & standards requirements of the platform and transfer them into engineering metrics and target values

This phase starts with the identification of the most important market and standard requirements for the four product families. QFD1 helps engineering to list the requirements and their relationship to engineering metrics. Items such as “efficient heating performance,” “low energy consumption” and “efficient space occupied” are a few examples of market and standard requirements for the platform (see Figure 30).

The engineering metrics for the various requirements are quantifiable items such as “heating power,” “power supply” and “volume”. They are the translation of qualitative requirements into quantitative technical specifications. In this step the engineering metric target values are determined for the different product families of the platform as shown on the bottom of the matrix (see Figure 31). The target values could be based on information from previuos projects, conjoint analysis, competitor product analysis and trend analysis of expected new markets.

From a cross-comparison of the various target values, the most variable requirements can be already identified with the support of a column added to the QFD-1 (see Figure 30). The range of change of the requirements is estimated through a simple rating scale (high/medium/low).

Market & Standards Requirements	Heating power (kW)	Cooling power (kW)	Power supply (V)	Fresh air flow (m3/h)	Volume (m3)	Sound pressure (dB)	Weight (kg)	Time (min)	Air pressure (Pa)	Cost (€)
	Engineering Metrics									
Efficient heating performance	**X**									
Efficient cooling performance		**X**								
Low energy consumption			**X**							
Regular fresh air flow				**X**						
Efficient space occupied					**X**					
Low noise						**X**				
Low weight							**X**			
Pressure pulse protection									**X**	
Fast maintenance								**X**		
Cost-efficiency per unit										**X**

Figure 30: First QFD matrix (own elaboration)

Market & Standards Requirements	Heating power (kW)	Cooling power (kW)	Fresh air flow (m3/h)	Volume (m3)	Sound pressure (dB)	Weight (kg)	Time (min)	Air pressure (Pa)	Cost (€)	Expected range of change in the platform
Efficient heating performance	**X**									H
Efficient cooling performance		**X**								H
Low energy consumption	**X**	**X**								M
Regular fresh air flow			**X**							M
Efficient space occupied				**X**						M
Low noise					**X**					H
Low weight						**X**				M
Pressure pulse protection								**X**		M
Fast maintenance							**X**			L
Cost-efficiency per unit									**X**	H
EM target values	**kW**	**kW**	**m3/h**	**m3**	**dB**	**Kg**	**min**	**Pa**	**€**	**Start**
HTS Coldline	**35**	**25**	2000	3	**60**	500	60	-250	25K	January 2015
Metro High-end	**30**	**20**	**4000**	**2,5**	**66**	**600**	60	**-100**	**22K**	January2015
HTS Hotline	**25**	**35**	**2000**	**3**	**57**	**500**	60	**-250**	**25K**	May 2015
Metro Low-end	30	20	4000	2,5	66	600	60	-100	**17K**	May 2017

Figure 31: First QFD matrix, including EM target values (own elaboration)

D. Map the engineering metrics to the components and identify the components of the platform that need higher level of redesign required to meet the different requirements

At this stage the engineering metrics are mapped to the main componenst that are used in the HVAC design. The mapping for the saloon HVAC example is shown in Figure 32. An “X” indicates that the component can affect the engineering metric. For example, the “air duct system,” “air supply fan” and “dampers” all have an impact on the “fresh air flow”.

	Components								
	Air duct system	Air supply fan	Dampers	Condenser unit	Heater	Compressor	Inverter	Temperature control unit	Insulation system
Engineering Metrics									
Heating power (kW)				X	X	X	X		
Cooling power (kW)				X	X	X	X		
Fresh air flow (m3/h)	X	X	X						
Volume (m3)	X			X	X	X			X
Sound pressure (dB)		X				X			X
Weight (kg)	X			X	X	X			X
Air pressure (Pa)		X	X						
Time (min)				X	X				
Cost (€)	X			X	X	X		X	X

Figure 32: Second QFD matrix (own elaboration)

After the completion of QFD-2 the GVI matrix can be created (see Figure 33). It is based on QFD-2 and helps engineering to estimate the cost of changing the component to meet the different EM target values. Components are rated through a 9/6/3/1 rating system that provides an indication of the component redesign cost and effort. For instance, the self-contained HVAC “volume” engineering metric starts at 3 m^3 for the HST segment and has its most stringent requirement of 2,5 m^3 for the Metro segment. The engineering team decises which of these components require a major or partial redesign in order to meet the more stringent target value. The estimation is based on the enginering expertise and judgement of the team. In this case, two senior HVAC expert engineers were involved in the methodological application. At this stage of the process, the GVI is calculated for each component by summing the relative rates. For the saloon HVAC example, the condenser unit (GVI = 24), the heater ((GVI = 24), the insulation system (GVI = 15) and the compressor (GVI = 14) are the components that have the higher percentage level of redesign required to meet the different specification across the four product families.

Engineering Metrics	Air duct system	Air supply fan	Dampers	Condenser Unit	Heater	Compressor	Inverter	Temperature control unit	Insulation system
	Components								
Heating power (kW)				6	9	3	0		
Cooling power (kW)				6		3	0		
Fresh air flow (m3/h)	1	1	1						
Volume (m3)	3			3	6	3			3
Sound pressure (dB)		1				1			6
Weight (kg)	1			3	3	1			3
Air pressure (Pa)			1						
Time (min)				0					
Cost (€)	1			6	6	3		1	3
GVI	6 L	2 L	2 L	**24 H**	**24 H**	**14 M**	0 L	1 L	**15 M**

Figure 33: GVI matrix based on QFD-2 (own elaboration)

E. Analyse the platform cost drivers to identify the economic potential of standardisation

At this phase of the methodology the experts have already identified the various external drivers of changing a design across the product families. However, to decide which components are worth to be standardised and which not, it is important to identify the cost structure of the HVAC subsystem. Different typologies of cost such as material cost, development and validation cost, supplier non-recurring cost can be used to estimate the cost drivers of the subsystem. In this example, as a matter of simplicity only the percentage of material cost is considered. From the analysis of different bills of material (BOM), the compressor and the temperature control unit result to be the main drivers of material cost (see Table 10). A standardisation of these components may lead to economies of scale and material cost reduction.

Component	% Cost of Material*
Air duct system	10%
Air supply fan	10%
Dampers	5%
Condenser Unit	10%
Heater	10%
Compressor	20%
Inverter	10%
Temperature control unit	20%
Insulation material	5%

* Average % cost of material of different project BOM

Table 10: Analysis of cost drivers (own elaboration)

F. Identify critical components for platform flexibility by analysing component coupling

As discussed in chapter 2.5.2.3 the changes required by external market and standard requirements may, in turn, require other internal changes in the design. These changes are caused by the interaction of the components with the design of the subsystem. CPI helps engineering to measure of change propagation of a single component. It measures the degree of physical change propagation caused by a component when an external change is imposed on the system. The method is based on a DSM to which two columns are added on the right and on the bottom to calculate the number of changes propagated or received by a component (see Figure 34). The numeric value “1” is given when a component propagates changes to or receives changes from another component. The sum of both received and propagated changes gives the CPI of each component. Depending on the value of the component (CPI<0; CPI>0; CPI=0), it can be an absorber, a multiplier or a carrier[405].

		Component PROPAGATING change													
		Air duct system	Air supply fan	Dampers	Condenser Unit	Heater	Compressor	Inverter	Temperature control unit	Insulation system	Carbody shell	Ceiling panels	Power supply	TCMS	ΔE in
Component RECEIVING change	Air duct system		1	1	1							1			4
	Air supply fan	1					1					1	1		4
	Dampers	1	1									1			3
	Condenser Unit	1					1				1	1			4
	Heater				1							1	1		3
	Compressor				1			1			1		1		4
	Inverter						1						1	1	3
	Temperature control unit			1							1		1		3
	Insulation material	1	1		1	1	1				1				6
	Carbody shell				1		1								2
	Ceiling panels	1	1		1	1									4
	Power supply						1		1						2
	TCMS								1						1
CPI	ΔE out	5	0	2	6	2	6	1	2	0	4	5	5	1	
	CPI	1	-4	-1	2	-1	2	-2	-1	-6	2	1	3	0	
	Class CPI	M	A	A	M	A	M	A	A	A	M	M	M	C	
GVI	Class GVI	L	L	L	H	H	M	L	L	M					
% Cost		10%	10%	5%	10%	10%	20%	10%	20%	5%					

Figure 34: CPI matrix, including external interconnected system parts (own elaboration)

[405] See 2.5.2.4 for the following description

On the bottom a row for the GVI and for the percentage of material cost is added to help engineering identifying the critical components for subsystem flexibility. Those components that show a high GVI and are multipliers or carriers are prime candidates for incorporating flexibility. These are elements that, as more changes are added, make the system harder to change. One must investigate elements connected to multiplier and carrier components to understand the nature of change. These elements might require flexibility- e.g. a ‘‘buffer’’ to absorb the change- to reduce or even eliminate change propagation altogether. For the HVAC example, the condenser unit and the compressor are multipliers and have high and medium GVI. This means that these components should remain variable to meet different external requirements but they should be stabilised in order to limit changes propagation to other components. In this example additional components are added to the original DSM matrix to identify the relationship between HVAC components and the main interconnected external subsystems. However, only the relationships between HVAC component and the main interconnected external subsystems are included and represented in this example. In fact, the scope of this exercise is limited to the HVAC and does not include the relationships between external subsystems.

G. Analyse the library of solutions to identify reusable concepts, components and methods

	Product 1	Product 2	Product 3
Supplier	Faiveley	Melco	Faiveley
HVAC unit type	Self-contained	Self-contained	Self-contained
Heating power	30	31	18
Cooling power	32	26	20
Insulation material	Aerogels	Melamine Foam with aluminium facing	Fibreglass/ Rockwool in aluminium bags
Pressure pulse protection	Variable speed fans	Dampers	No
Inverter	YES	Yes	No
Fresh air flow	2500	4000	3000
Volume	2,7	3	2
Weight	600	550	700
Control voltage	110 vdc	110 vdc	110 vdc
Compressor type	Screw	Screw	Reciprocating
Compressor capacity control	On/off	Variable speed	On/off
Sound level	66 dB	57 dB	63 dB
Cost Unit	25K	23K	21K
Power supply voltage	440V/3ph/60Hz	440V/3ph/60Hz	440V/3ph/60Hz
Carbody shell material	Steel	Aluminium	Aluminium
Carbody shell integration	Roof-mounted	Roof-mounted	Roof-integrated
		Selected	

Table 11: Example of library of solutions (own elaboration based on BT confidential data)

Table 11 shows an example of library of technical solutions where products containing components, concepts, methods and material identified as preferred solutions for standardisation are listed. It is important to clarify that these solutions can be either reused as they are or readapted to the market requirements of the platform. For the HVAC example, “product 2” has been selected as a technical baseline to develop the subsystem platform. Technical solutions such as the insulation material “melamine foam with aluminium facing” or the “screw compressor with variable speed” will be used in the new product families (in green).

H. Selected and involve preferred suppliers in the JDDP process by defining the type of design collaboration.

The results of library of solutions are used as a baseline for the development of the technical solution. Since BT operates in a design network, the design activity are performed together with the suppliers or completely outsourced. Firstly, the lead buyer together with the lead engineer should define the most appropriate supplier involvement approach for the subsystem. The decision should consider BT and supplier capabilities, complexity of the subsystem, development risk and the importance of the subsystem forma strategic point of view. Once the type of collaboration is defined, the preferred suppliers are invited to a kick-off meeting and are asked to propose their solutions in relation to the subsystem performance goals defined by the platform team. The different supplier solutions are evaluated and only two suppliers are selected and involved in the design and development of the subsystem for the platform through the JDDP process (see Annexure 5).

The JDDP is based on the application of the following tasks:

1. Establishing a long-term strategy and relationship with preferred suppliers
2. Pre-agreed design rules and interfaces – with consequently fewer iterations, reworks and changes
3. Physically co-locating the preliminary design team as instructed by the Project Core Team directive

If the suppliers are involved through a black box approach only task 1 and 2 are performed because once the design rules and interfaces are agreed together, the suppliers can proceed to design and develop the subsystem alone by respecting design rules, interfaces and performance goals.

Alternatively, if the suppliers are involved through a grey box approach all 3 tasks are performed and BT and the two selected suppliers work together to define the technical solution

I. Select the design concepts to stabilise the critical components and to define which components of the platform remain stable and which variable.

At this point, the platform engineering team and the two selected suppliers work together to stabilise the critical components and to ensure changeability and flexibility of the platform. The Hierarchic Layer Analysis supports the concept selection activity and the interface definition through a simple table as a framework (see Table 12).

		Hierarchic Layer Analysis			
		Predefined functions & components	**Variable functions & components**	**System Layout**	**System Integration**
Internal	Air duct system (to be developed)	Predefined ducting, filters, grids and air circulation	Variable material according to material cost and weight. Ex. Aluminium or fabric. Additional ducts to low level	Predefined solution in the ceiling to limit testing, trade-off space constraint. Ex. Side ducts or central ducts	Predefined physical interface with the ceiling
	Air supply fan (available)	Predefined type and size		Predefined position of the cabinet	
	Dampers (available)	Predefined option for pressure pulse protection instead of Variable speed fan for HST segment		Predefined position in the ceiling	Same plug-in of the dampers
	Condenser Unit (Condenser 1 available; condenser 2 & 3 to be developed)		Variable component depending on the cooling/heating capacity. Variable condenser fan and power	Predefined position of the cabinet in the car	Predefined integration method of the cabinet to the carbody shell
	Heater (to be developed)		Variable component depending on the heating capacity. Ex. fans heathers, convectional heater or underfloor heater		
	Compressor (compressor 1 available; compressor 2 to be developed)	Predefined screw compressor for HST segment, inverter needed for the different climatic zones	Predefined reciprocating small compressor without inverter option		Predefined electrical interface. Ex. voltage, frequency, AC/DC
	Inverter (available)	Predefined option for lower energy consumption and power capacity adaptability			Predefined electrical interface. Ex. voltage, frequency, AC/DC
	Temperature control unit (available)	Predefined TCU unit with modular software	Additional software module for GPS and CO2 detection in HST segment	Predefined self-contained solution in the HVAC unit	Predefined Functional interface protocol with TCMS

	Insulation material (available)		Variable material according to insulation performance, cost and weight		Compatible material with carbody shell solution

Table 12: Hierarchic Layer Analysis of the subsystem with focus on critical components (own elaboration)

The scope of this exercise is to select design concepts that reduce the sensitivity of the components to changes in the specifications by "freezing" the component interface. For example, to meet different cooling and heating performance with same compressor, an inverter can be used to regulate the frequency and the voltage of the compressor. However, this implies that the product families that include such compressor must have always the same standardised electrical configuration to use the predefined compressor and inverter.

This explains why not only the internal HVAC components are analysed but also the main external subsystems and parts that interface with the HVAC (see Table 13). According to the EM target values the design solutions are selected from the library of solutions. As mentioned above the solutions can be reused as they are or adapted to the requirements of the platform. Only if the design concepts or the technical solutions are not available in the library of solutions, they are developed from scratch in collaboration with the selected suppliers

		Hierarchic Layer Analysis			
		Predefined functions & components	**Variable functions & components**	**System Layout**	**System Integration**
External	**Carbody Shell** (available	Predefined material for every vehicle. Ex. Aluminium	Variable design, shape and size	Predefined layout position of the HVAC unit and air duct system	Predefined physical integration method
External	**Ceiling panels** (to be developed)	Scalable ceiling panels	Variable design, material, thickness	Predefined layout position of the cabinets and common components	Predefined physical integration method
External	**Power supply** (available)	Predefined electrical configuration			Predefined electrical interfaces. Ex. voltage, frequency, AC/DC
External	**TCMS** (to be developed)	Common train control system software with modular architecture			Predefined functional interface protocol interface and compatibility with power supply

Table 13: Hierarchic Layer Analysis of the external parts that interface with the subsystem (own elaboration)

Finally, once the design concepts are selected, the platform team define which components are commonly shared by the four product families, which components are shared in some product families and differentiated in others and which components remain variable across all the product families (see Figure 35). For instance, the “air duct system”, the “Temperature Control Unit (TCU)” and the “air supply fan” are shared across the four product families and form the core part of the platform, whereas the “heather” is only shared by the HST Coldline and the Metro High-end or the solution combining compressor and inverter is only shared by the HST Hotline and the HST Coldline. Table 14 shows the degree of commonality shared across the product families. For example, Product Family 2 (PF2) has 70 % of the components in common with product family 1 (PF1) but only 40% of the components in common with Product Family 4 (PF4).[406]It is important to remark that even though interface specifications can be standardised and components can be overdesigned without any design change, a possible disadvantage of increasing specification “headroom” is that the material cost may increase. In the HVAC example, different insulation systems are selected for Metro High-end and Metro Low-end because the second product family is more sensible to material cost. This may lead the platform team to sacrifice the reuse of the same insulation system for adopting a cheaper insulation system tailored to the needs of the Metro Low-end product family.

The example shows how making good platform decisions require making complex trade-offs in the planning and the design phase of their development.

Product family commonality			
Product family	**Commonality rate**		
PF1			
PF2	70% PF1		
PF3	50% PF2	40% PF1	
PF4	70% PF3	40% PF2	40% PF1

Table 14: Example of commonality rate of the product families (own elaboration)

[406] For the following description see Boas, 2008

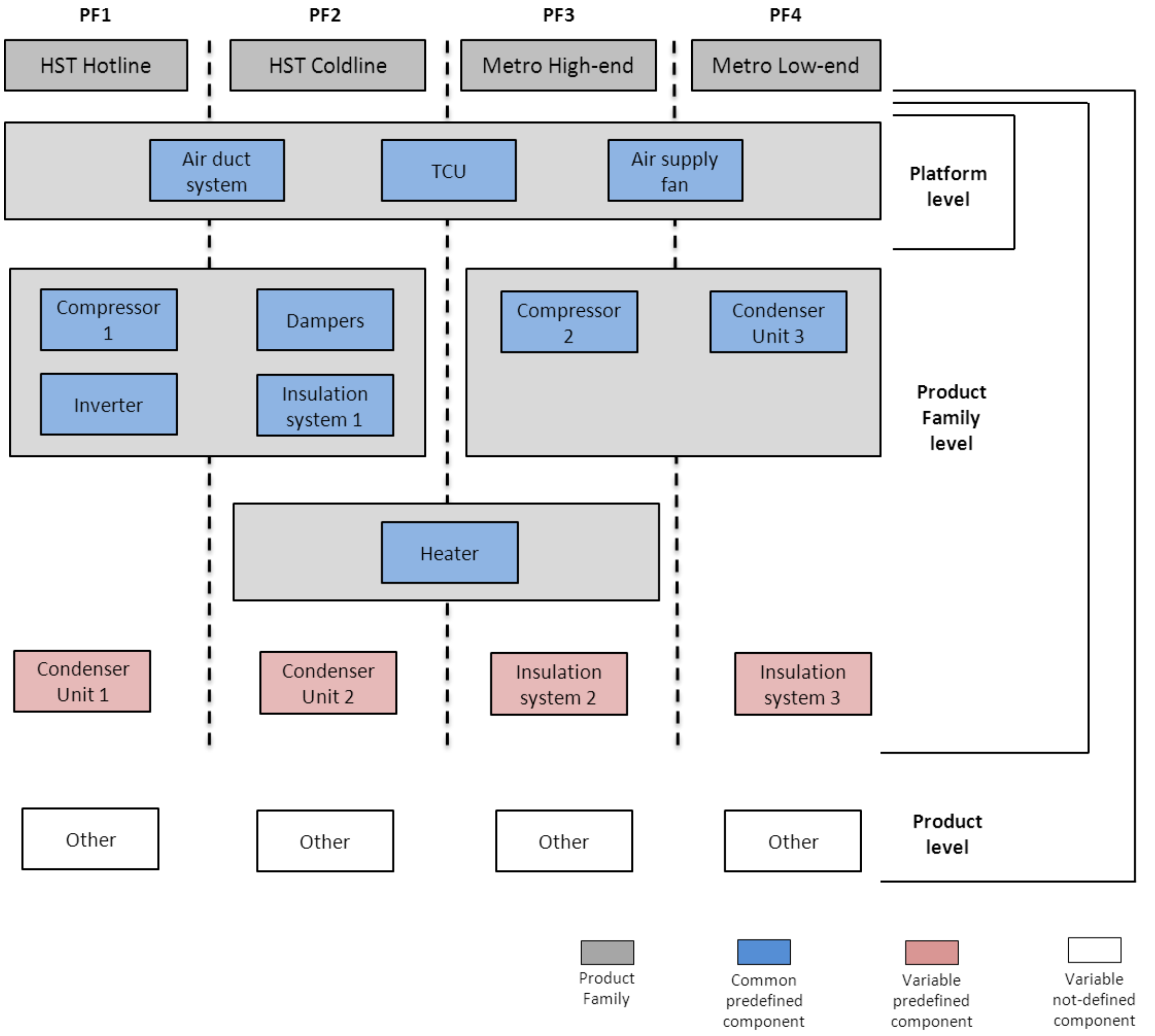


Figure 35: Common and variable components predefined within the product families (own elaboration)

7. Discussion: investigating platform development characteristics in a customisation-driven context

7.1. Conclusion: rolling stock development as a complex environment to identify platform potential

Rolling stock has been widely neglected in the research and discussion of platform development. As described throughout this thesis, the fact that these products are developed and produced in a project-driven customised environment and in relative low product volume makes the potential for platform development and commonality strategies difficult and challenging. However, the continuous evolution and transformation of the worldwide rolling stock market, including increasing competition and new business opportunities in emerging countries is pushing rolling stock providers to shift their project-oriented product development to platform-based product development.[407] The complexity of the industry and its natural adversity to standardisation make the identification of platform potentials and platform development characteristics often different from a case to another also within the same company. For instance, *Flexity2* platform is based on the reuse of physical parts and mechanical platform configuration, whereas *TRAXX* focuses more on reusing functionality across the various product families.[408]

This research grounds the theoretical foundation of platform development characteristics of rolling stock starting from the research area of CoPS. Although many similarities have been identified between CoPS and rolling stock in the various aspects of product complexity and in the platform planning and design characteristics, the rolling stock environment remains a *sui generis* context to develop platforms. In all the "platform" case studies common development challenges were identified. These are: the variety of standards and market requirements, the differences in the various rolling stock segments, the technical complexity of the systems and the project-oriented nature of the product development.[409] To face these challenges it is clear that different compromises about the development of platforms with regard to flexibility of product family design, the efficiency of product realisation and the effectiveness of product positioning have to be considered.[410] A careful market segmentation and distinction of which components, concepts, configurations and methods can be shared and which parts can remain variable are the crucial activities of any new platform development. However, the case studies showed how such activities are difficult to implement in a similar environment. The platform planning and design methodology seeks to turn rolling stock platform development characteristics into a systematic process. The process involves not only BT but also the main component suppliers selected to be part of the design network of the platform-based projects. Across the case studies suppliers result

[407] See Railway Gazette International, July 2014, p. 40
[408] See Flexity2 (1,2); TRAXX (2)
[409] See BiLevel (1,2), TRAXX (1,2); Fleixity2 (1,2); Aventra (1,2); CTO (1,4,6)
[410] See Hofer and Halman, 2005, p. 257

to be mainly involved through long-term agreements based on a grey box and black box design collaboration. The type of collaboration mainly depends on the strategic importance of the subsystem for the buying company.[411]Although all the platform development projects recognised the necessity of supplier involvement in platform development, BT results to be not mature enough and experienced in establishing strategic partnership with suppliers and managing the relationship in a design network.[412] This also confirmed by the lack of a specific BT process aimed at guiding the design and development collaboration with suppliers within the multi-project view of the platform strategy. In building and defining the platform planning and design methodology, the author sought to extend part of the methodology also to the main suppliers that collaborate with BT in the design network. As a result the integration of the different methodologies from the literature and from the case studies in a unique method will help engineering at BT to systematically plan and design modular platforms in a design network.

7.2. Managerial recommendations for rolling stock and CoPS providers: integrating cross-functionally and centralising decision-making to enable a common technical reuse

Although this research is focused on BT and the business context of rolling stock providers, managerial implications can also be derived for those companies that operate in CoPS environments. Firstly, the migration of a company to a platform-based product development implies the creation of a new organisational structure where marketing & sales, procurement and engineering can collaborate and work cross-functionally.[413] These synergies are essential to identify market requirements, strategic co-developer suppliers and technical capabilities limits. Secondly, a centrally-led platform management should be responsible to coordinate the different functions, including committing engineers to use the platform in the customer-projects and maintaining the platform throughout the entire lifecycle. This often requests platform managers to change the attitude of those engineers that are “affected” by the “not invented here” syndrome and that seek to reuse only those solutions developed in their engineering sites.[414] Especially for engineering sites in large and dispersed multinationals like BT, it is difficult to ensure that all the projects will share a common technical base, because it is very likely that engineers and sales will try to deviate from the original platform to meet specific customer requirements and apply favourite technical solutions.[415] To facilitate the reuse of common platform solutions and capabilities, it is important to centralise the decision-making processes of the platform

[411] See TRAXX (3); Flexity2 (3), Aventra (3)
[412] See BiLevel (3); TRAXX (3); Flexity2 (3), Aventra (3)
[413] See Aventra (2); CTO (2,4,5)
[414] See CTO (3,4)
[415] See Flexity2 (1); TRAXX (2); CTO (5)

development such as supplier sourcing. Furthermore, to ensure that the supply-base management takes into account the well-being of the entire platform life-cycle and not only the particular project, it is highly recommended to segregate the purchasing function in two responsibilities: advanced sourcing and life-cycle sourcing.[416] While the first should consists of professional with an engineering background and should support the design collaboration between platform engineering and suppliers in platform development, the life-cycle sourcing should be formed by professionals with a commercial background and should have the overall responsibility for supplier selection and management across the projects. [417]

Limitation and further research: more research needed in the field of rolling stock and CoPS platforms

The major limitation of the present research has been mentioned before and consists of the limited generalisation of the empirical findings due to the lack of external validity. In fact the study focuses only on one company even though different platform development projects are analysed. In addition, several potential sources of bias need to be acknowledged. Firstly, the higher number of interviews conducted for the CTO-led platforms case study and the active participation of the author in the CTO's activities may lead to certain biases in the analysis of the empirical results. Bias may also be introduced by researcher's inexperience with the application of the case study method. However, the exploratory nature of this research makes the methodological flaws less weighty. The goal of this study was to identify platform development characteristics of rolling stock and to develop a systematic platform planning and design methodology in the context of BT. The case study sheds light on issues that have been neglected or not received sufficient attention in prior literature by suggesting directions of further research.

Firstly, due to the relatively low volumes in rolling stock companies the main driver for platform-based product development should not be economies of scale. Additional drivers may be found in the reuse of platform concepts, processes, methods, tools and know-how. As pointed out also by Gunzenhauser[418], future research should investigate the benefits of such nonphysical platforms and help making them quantifiable.

Secondly, the concept of platform-based product development needs to be closely linked with a clear understanding of costs and benefits. Therefore future work should investigate methods that help identify source of cost saving, including different types of cost such as material cost, nonrecurring engineering cost, integration and assembly cost, lifecycle cost that should be attributed to developing and maintaining a platform.

[416] See Schiele, 2010, pp. 146-147
[417] See Schiele, 2010, pp. 146-147
[418] See Gunzenhauser, 2007, p. 194

Thirdly, to contribute to the advancement of supplier involvement in platform development, future research should investigate and identify both successful and failure factors of buyer-supplier collaboration in platform-based projects.

Following the research on platform potential in CoPS initiated by Hofer and Halman[419], this research contributes not only to the use of rolling stock as a research area of platform development but also to expand the investigation on the development of platform-based product families and products of CoPS. In particular, a validation of the platform planning and design characteristics of rolling through further research in varying corporate environments would extend the generalisation of the research's findings.

Finally, the application of the platform planning and design methodology to clusters of interconnected rail subsystems or to an entire rail vehicle will provide enriched knowledge about its practical effectiveness on platform development.

[419] For the following description see Hofer and Halman, 2005

List of references

1. **Adachi, M. (2013).** Case Study: China South Locomotive and Rolling Stock Corporation (CSR). *China's Competitiveness: Myth, Reality, and Lessons for the United States and Japan*.

2. **Akao, Y., (1990).** *Quality Function Deployment*, Productivity Press, Cambridge MA.

3. **Van Aken, J. E., Berends, H., & van der Bij, H. (2007).** *Problem Solving in Organizations*. Cambridge: Cambridge University Press.

4. **Avak, B. (2007).** *Variant Management of Modular Platform Products in the Market Phase.* Ph.D. Thesis, ETH Zurich.Boas, R.C. (2008). Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets. Massachusetts Institute of Technology.

5. **Babbie, E. (2010).** *The Practice of Social Research*. Wadsworth: Cengage Learning.

6. **Baldwin, C. Y. & Clark, K. B. (2004).** Modularity in the Design of Complex Engineering Systems. Harward Business School. Working paper

7. **Baldwin, C. Y. & Woodard C. J. (2008).** *The Architecture of Platforms: A Unified View*. Woking paper, 09-034

8. **Baxter, P., & Jack, S. (2008).** Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13(4), 544–559.

9. **Blumberg, B., Cooper, D. R., & Schindler, P. S. (2011).** *Business Research Methods*. London: McGraw-Hill Education.

10. **Boas, R.C. (2008).** *Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets.* Massachusetts Institute of Technology.

11. **Bonaccorsi, A. & Lipparini, A. (1994).** Strategic Partnerships in New Product Development:an Italian Case Study, Product Innovation Mnagement, 11, 134-145

12. **Bongulielmi, L.** (2002). Die Konfigurations- & Verträglichkeitsmatrix als Beitrag zur Darstellung konfigurationsrelevanter Aspekte im Produktionsentstehungsprozess, ETH Zurich.

13. **Bowman, D. (2006).** *Effective Product Platform Planning in the Front End.* In: Simpson, T. W., Siddique, Z. and Jiao, J. (2006). *Product Platform and Product Family Design*. Springer.

14. **Brady, T. (2002).** *Utilization of Dependancy Structure Matrix Analysis to Assess Implementation of NASA's Complex Technical Projects.* M. S. Mechnaical Engineering, MIT, Boston.

15. **Cameron, B. G. & Crawley, E. F. (2013).** *Crafting Platform Strategy Based on Anticipated Benefits and Costs.* In: Simpson, T. W., Jiao, J., Siddique, Z. & Hölttä-Otto, K. (Eds.). *Advances in Product Family and Product Platform Design: Methods & Applications*, Springer, New York

16. **Campos, J & Cantos, P (1998).** *Rail Transport Regulation*. Economic Development Institute of the World Bank.

17. **Chen, D.Q., Preston, D.S. & Xiab, W. (2013).** Enhancing hospital supply chain performance: A relational view and empirical test, *Journal of Operations Management*, 31, 391–408

18. **Chen, K. M. & Liu, R. J. (2005).** Interface strategies in modular product innovation. *Technovation*, 25, 771–782

19. **Collier, D. A. (1981).** The Measurement and operating benefits of component part commonality. *Decision Sciences*, 12, 85-96.

20. **Corso, M., Martini, A., Paolucci, E. & Pellegrini, L. (2001).** Knowledge management in product innovation: an interpretative review. *Journal of Management Reviews,* 3(4), 341–352

21. **Davies, A. & Hobday, M. (2005).** *The Business of Projects: Managing Innovation in Complex Products and Systems*. Cambridge: Cambridge University Press.

22. **Eisenhardt, K. (1989).** Building Theories from Case Study Research. *The Academy of Management Review*, 14(4), 532–550.

23. **Eisenhardt, W. H., & Graebner, M.E. (2007).** Theory Building from Cases: Opportunities and Challenges. *Academy of Management Journal*, 50(1), 25-32.

24. **ElMaraghy H (2009).** Changing and Evolving Products and Systems – Models and Enablers, in Changeable and Reconfigurable Manufacturing Systems. In Editor H, (Ed.) ElMaraghy, Springer-Verlag, London.

25. **H. ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P.,Tseng, M. & Bernard, A. (2013).** Product variety management. *CIRP Annals - Manufacturing Technology*, 62, 629–652.

26. **EMCC- European Monitoring Centre on Change (2004).** Trends and drivers of change in the European railway equipment sector. Report. Dublin

27. **Van Echtelt, F. E., Wynstra, F., van Weele, A. J., & Duysters, G. (2008).** Managing Supplier Involvement in New Product Development: A Multiple-Case Study. *Journal of Product Innovation Management*, 25(2), 180–201.

28. **Erzner, M. (2007).** *Life Cycle Quality Function Deployment - An Integrated and Modular Approach.* Produktentwicklung und Maschinenelemente

29. **Fan, B., Qi, G., Hu, Xiaomei, H., & Yu, T. (2013).** A network methodology for structure-oriented modular product platform planning. *J. Intell Manufacturing.*

30. **Feng, T., Sun, L. & Zhang, Y. (2010).** The effects of customer and supplier involvement on competitive advantage: An empirical study in China. *Industrial Marketing Management*, 39, 1384–1394

31. **Fricke, E. & Schulz, A. P. (2004).** Design for Changeability (DfC): Principles To Enable Changes in Systems Throughout Their Entire Lifecycle. *Systems Engineering*, 8 (4), 342-359

32. **Gassmann, O. (2003).** Lieferanten als Innovationsquelle in F&E [Suppliers as source of innovation in R&D]. In R. Boutellier, S. M. Wagner, & H. P. Wehrli (Eds.), *Handbuch Beschaffung*. München: Hanser.

33. **Gil, N. (2007).** On the value of project safeguards: Embedding real options in complex products and systems. *Research Policy,* 36, 980–999

34. **Gunzenhauser, M. (2007).** *Platform Concept for the System Business: Design and Development of Global Product Platforms*. Institute of Machine Tools and Manufacturing

35. **Halman, J.I.M., Hofer, A.P. & Vuuren, W. (2006).** *Platform-driven development of product families, linking theory with practice*, In: Simpson, T.W., Siddique, Z. and Jiao, R. (2006). *Product Platform and Product Family Design: Methods and Applications*, Springer.

36. **Hobday, M. (1998).** Product complexity, innovation and industrial organisation. *Research Policy*, 26, 689-710

37. **Hobday, M. (2000).** The project-based organisation: an ideal form for managing complex products and systems? *Research Policy*, 29, 871–893

38. **Hofman, E., Voordijk, H. & Halman, J. (2009).** Matching supply networks to a modular product architecture in the house building industry. *Building Research & Information,* 37(1), 31-42

39. **Hölttä-Otto, K. (2005).** *Modular Product Platform Design.* Doctoral Dissertation. Helsinki University of Technology, Helsinki

40. **Hoetker, G., 2005.** How much you know versus how well I know you: Selecting a supplier for a technically innovative component. *Strategic Management Journal*, 26, 75-96.

41. **Hofer, A. P. & Halman, J. I. M. (2005).** The potential of layout platforms for modular complex products and system. *Journal of Engineering Design*, 16 (2), 237–258

42. **Holland, J. (1999).** Emergence: from chaos to order. Cambridge. MA: Perseus

43. **Hsuan, J. (1999).** Impacts of supplier-buyer relationships on modularization in new product development. *European Journal of Purchasing & Supply Management*, 5, 197-209

44. **Kannan, V.R. & Tan, K.C. (2002).** Supplier Selection and Assessment: Their Impact on Business Performance', *Journal of Supply Chain Management, 38 (4), 2002*

45. **King, N. (2004).** *Using interviews in Qualitative research.* In: Cassell, C. & Simon, G. (Eds). (2004. Essential guide to qualitative methods in organisational research. Sage.

46. **Kleissl, J. (2004).** Gestaltung von Produktornungsystemen: Methoden zur Schaffung marktgerechter Produktprogramme. 30 TCW.

47. **MacDonald, L. (2013).** *The Bombardier story: from snowmobiles to global transportation powerhouse*. Mississauga: Wiley.

48. **Magnusson, M. & Pasche, M. (2014).** A Contingency-Based Approach to the Use of Product Platforms and Modules in New Product Development. *Journal Product Innovation Management*, 31(3), 434–450

49. **Martin MV, Ishii K (2002).** Design for variety: developing standardized and modularized product platform architectures. *Research Engineering Design*, 13 (4), 213-135

50. **McGrath, M. (1995).** *Product Strategy for High-Technology Companies. How to Achieve Growth, Competitive Advantage, and Increased Profits*. USA: McGraw-Hill.

51. **Meyer, M.H. & Lehnerd, A.H. (1997).** *The Power of Product Platform*. The Free Press, New York.

52. **Mietzner, D. & Reger, G. (2005).** Advantages and Disadvantages of Scenario Approaches for Strategic Foresight. *International Journal Technology Intelligence and Planning*, 1 (2), 220-239.

53. **Mikkola, J. H. (2006).** Capturing the Degree of Modularity Embedded in Product Architectures. *Journal of Product Innovation Management*, 23, 128-146

54. **Miller, D. T. & Elgärd, P. (1998).** *Defining Modules, Modularity and Modularisation.* Design for Integration in Manufacturing. Proceedings of the 13th IPS Research Seminar, Fuglsoe 1998

55. **Möller, K. E., & Törrönen, P. (2003).** Business suppliers' value creation potential: a capability-based analysis. Industrial Marketing Management, 32(2), 109-118.

56. **Monczka, R.M., Handfield, R.B., Scannel, T.V., Ragatz, G.L., Frayer, D.J. (2000).** *New product development: Strategies for supplier integration*, Milwaukee: ASQ Quality Press.

57. **Monczka, R. M., Handfield, R. B., Giunipero, L., Patterson, J., & Waters, D. (2010).** *Purchasing and Supply Chain Management*. Andover (Hampshire): Cengage Learning EMEA.

58. **Muffatto, M & Roveda, M. (1998).** Product structures and new product development strategy, *Proceedings of the 10th International Working Seminar on Production Economics*, 16-20.

59. **Muffatto, M. (1999).** Introducing a platform strategy in product development. *Int. J. Production Economics,* 60, 145-153.

60. **Pellegrini, P. & Rodriguez, J. (2013).** *Single European sky and single European railway area: A system level analysis of air and rail transportation*. Transportation Research Part A: Policy and Practice, 57, 64-86

61. **Petersen, K.J., Handfield, R.B. & Ragatz, G.L. (2005).** Supplier integration into new product development: coordinating product, process and supply chain design, *Journal of Operations Management*, 23, 371–388

62. **Pimmler, T. & and Eppinger, S. (1994).** *Integration analysis of product decomposition*. ASME Design and Methodology Conference, Minneapolis.

63. **Porter, M. E.** (1986). *Competition in Global Industries.* Harvard Business Press.

64. **Prencipe, A. (1998).** Modular Design and Complex Product Systems: Facts, Promises, and Questions. *CoPS Publ. 47*, 1-23.

65. **Roland Berger Strategy Consultants (2012).** *UNIFE World Rail Market Study 2012*. Brussels: UNIFE

66. **Quinlan, C. (2011).** *Business Research Methods*. Andover (Hampshire): Cengage Learning EMEA.

67. **Ragatz, G. G. L., Handfield, R. B., & Scannell, T. V. (1997).** Success factors for integrating suppliers into new product development. *Journal of Product Innovation Management*, 14(3), 190–202.

68. **Railway Gazette International (2013).** May 2013.

69. **Railway Gazette International (2014).** July 2014.

70. **Ratamaki, K. (2004).** *Product Platform Development from the Product Lines' Perspective: Case of Switching Platform.* Doctoral thesis, Lappeenranta University of Technology

71. **Röckle, F. (2013).** *Harnessing Innovations Pushed from Suppliers: an Exploratory Study in the Railway Supply Chain.* Master thesis. University of Twente

72. **Robertson, D. & Ulrich, R. (1998).** Planning for Product Platforms. *Sloan Management Review*, 39(4), pp. 1-13.

73. **Rosell, D. T., & Lakemond, N. (2012).** Collaborative innovation with suppliers: a conceptual model for characterising supplier contributions to NPD. International Journal of Technology Intelligence and Planning, 8(2), 197-214.

74. **Ruuska, I., Ahola, T., Martinsuo, M., and Westerholm, T., (2013).** Supplier capabilities in larger shipbuilding projects. *International Journal of Project Management*, 31, 542-553.

75. **Sanchez, R. (2000).** Using modularity to manage the interactions of technical and industrial design. *Design Management Journal Academic Review*, 8-19

76. **Saunders, M., Lewis, P. & Thornhill, A. (2009).** Research Methods for Business Students. Pearson

77. **Schiele, H. (2006).** How to distinguish innovative suppliers? Identifying innovative suppliers as new task for purchasing. *Industrial Marketing Management,* 35(8), 925–935.

78. Schiele, H. (2010). Early supplier integration: the dual role of purchasing in new product development. *R&D Management,* 40(2), 138-153

79. **Schilling, M. A. (2000).** Toward a General Systems Theory and its Application to Inter-firm Product Modularity. Academy of Management Review, 5 (2), 312- 334

80. **SCI Verkehr (2014).** Worldwide rolling stock manufacturers. Annual report. Cologne

81. **Simon, H.** (1995). *Near decomposability and complexity: How a mind resides in a brain.* In: Morowitz, H. & Singer, J. (Eds.). *The mind, the brain and the complex adaptive systems. SFI studies in the science of complexity*. Addison-Wesley.

82. **Simpson, T. W., Bobuk, A., Slingerland, L. A., Brennan, S., Logan, D. & Reichard, K. (2012).** From user requirements to commonality specifications: an integrated approach to product family design. *Research Engineering Design*, 23, 141–153

83. **Simpson, T. W., Siddique, Z. and Jiao, J. (2006).** *Product Platform and Product Family Design*. Springer.

84. **Sköld, M. & Karlsson, C. (2013).** Stratifying the Development of Product Platforms: Requirements for Resources, Organization, and Management Styles. *Journal of Product Innovation Management*, 30 (1), 62-76.

85. **Sosa, M. E., Eppinger, S. D. & Rowles, C. M. (2003).** Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions. *Transactions of the ASME*, 125, 240-252.

86. **Steiner, R. (1999).** *Enduring system architectures*, Proc 10th Int Symp INCOSE, Brighton.

87. **Steward, D. V. (1981).** *Systems Analysis and Management: Structure, Strategy and Design*, PBI. A Petrocelli Book, New York.

88. **Suh, E. S., de Weck, O. L. & Chang, D. (2007).** Flexible product platforms: framework and case study. Research Engineering Design, 18, 67-89.

89. **Taguchi, G. (1993).** *Taguchi on robust technology*. ASME Press, New York.

90. **Tamaskar, S., Neema, K. & DeLaurentis, D. (2014).** Framework for measuring complexity of aerospace systems. *Research Engineering Design*, 25, 125-137

91. **Ulrich, K. (1993).** The role of product architecture in the manufacturing firm. *Research Policy*, 24, 419-441

92. **Ulrich, K.T. & Eppinger, S.D. (1995).** *Product Design and Development*, Mc Graw-Hill, Inc

93. **Ulrich, K.T. & Eppinger, S.D. (2012).** *Product Design and Development*, Mc Graw-Hill International Edition

94. **UNIFE (2010).** *World Rail Market Study: Status quo and Outlook 2020.* Brussels.

95. **UNIFE (2012).** *World Rail Market Study: forecast 2012 to 2017.* Brussels.

96. **UNIFE (2013).** *Annual Report 2012*. Brussels.

97. **Utterback, J. M. & Meyer, M. H. (1993).**The product family and the dynamics of core capability. *Sloan Management Review*, 34: 29-47.

98. **Wong, J. M. (2011).** A Relational View of Resources-based Theory: The case of Internationalization of Li & Fung Group, *The Journal of Human Resource and Adult Learning*, 7(2), 34-39

99. **Yassine1, A. A. & Wissmann, L.A. (2006).** The Implications of Product Architecture on the Firm. *Systems Engineering,* 10 (2), 117-137

100. **Ylimaki, J. (2014).** A dynamic model of supplier–customer product development collaboration strategies. *Industrial Marketing Managemen,* 1-9

102. **Yin, R.K. (2009).** *Case study research: Design and methods* (Vol 5). SageV.

103. **Zha, X.F. & Sriram, R.D.** (2006). Platform-based product design and development: A knowledge-intensive support approach. *Knowledge-Based Systems*, 19, 524–546

APPENDIX

Annexure 1: List of referenced internal documents and conversations

	Document Type	Document description
BT-Doc 2007	Product brochure	Presentation and description of *BiLevel* platform
BT-Doc 2009	Product brochure	Presentation and description of *Flexity2* platform
BT-Doc 2011	Product brochure	Presentation and description of *Aventra* platform
BT-Doc 2012	TRD	Technical description of *Aventra* platform
BT-Doc 2013	Product brochure	Presentation and description of *TRAXX AC3* platform
BT-Doc 2014a	Financial report	BT Annual report 2013
BT-Doc 2014b	Communicate	Description of BT business on the corporate website
BT-Doc 2014c	PPT Presentation	Presentation on BT engineering sites worldwide
BT-Doc 2014d	Communicate	Description of *OneBT* strategy and objectives
BT-Doc 2014e	Communicate	Description of new BT organisational structure
BT-Doc 2014f	Communicate	Description of BT obstacles to better performance
BT-Doc 2014h	Communicate	Description of CTO responsibility and objectives
BT-Doc 2014i	PPT Presentation	Presentation on Inventory Taking

	Date	Contact	Function
BT-Iben 2014b	04.04.2014	Dirk Iben	Platform Manager
BT-Iben 2014a	12.05.2014		

Annexure 2: Comparative case study- transcription of interviews
Platform Manager / Engineer Interview guideline type A

CONFIDENTIAL

Annexure 3: Comparative case study- transcription of interviews

Platform Lead Buyer Interview guideline type B

CONFIDENTIAL

Annexure 4: Platform Manager / Engineer interview guideline Type A

Purpose	Details of the interview
Introduction	Introduction to the research
	Reassurance of anonymity
	Question whether recording is allowed
	Introductory questions about the interviewee
Alignment of definitions	What do you understand under the term "platform"?
	What do you understand under the term "modularity"?
	What do you understand under the term “platform planning and design”?
General understanding of the platform development process and the consequent benefits	Does your unit have a platform development process? Could you briefly describe it?
	What are the benefits of implementing platform-based product development?
Investigating on aspects of product complexity	Could you briefly describe the degree of complexity of rail rolling stock?
	How does this complexity limit the development of a platform?
Understanding the role of product architecture and its characteristics	Which characteristics should a platform architecture have in order to limit rolling stock complexity?
	Which are the most important criteria in designing the platform architecture?
	Do you know (or apply) specific methodologies or tools for splitting, combining and modularising products, components and functions? Please provide related documents.
	Which are the main technical constraints and challenges in clustering the components into modules?
Understanding component interface definition	Do you know (or apply) a specific methodology to define and select the interfaces within and between the components?
	Which are the main technical challenges and constraints in defining component interfaces?
Understanding platform´s influence on organisational structure and product development collaboration	Which are the internal and external actors and how should they be integrated in platform development?
	How does the development of a modular platform influence the organisational structure and the intra/inter firm collaboration?
Understanding the handover of the platform to customer-project	One challenge of the platform development process is to maintain the platform intact and ensure that the derivative products will share high commonality. How can you guarantee high product commonality?

Closing	Asking the interviewee whether they think that an important issue was not covered in the interview
	Expression of thanks
	Expression of commitment to keep the interviewee posted about the finding of the study

Annexure 5: Platform Lead Buyer interview guideline Type B

Purpose	Details of the interview
Introduction	Introduction to the research
	Reassurance of anonymity
	Question whether recording is allowed
	Introductory questions about the interviewee
General motivation for supplier involvement	Why did you involve suppliers in the platform development project?
Different types of supplier-buyer relationship: Supplier characteristics, reason for different supplier involvement, success & failure factors	What kind of key characteristics, skills and competences do suppliers need to be involved in your company in the development activity as: (1) Producing supplier (White Box) (2) Co-developing supplier (Grey Box) (3) Designing and developing supplier (Black Box)?
	Can you please explain why and under which circumstances you apply or would apply: (1) No involvement of supplier (2) White Box (3) Grey Box (4) Black box
	What are the experience concerning the success factors of supplier involved in a: (1) White Box (2) Grey Box (3) Black box
	What are the experience concerning a failure with the involvement of a supplier in: (1) White Box (2) Grey Box (3) Black box
Buyer-supplier power & influence position in regards to interface specification	Can you please explain how you define and manage interface specification in regards to supplier integration?
	Can you describe your power of influencing suppliers interface specifications in the platform project?
	How do you deal with risk of reliance, e.g. if a supplier takes a system development role which can increase your dependency and his bargaining position?
Closing	Asking the interviewee whether they think that an important issue was not covered in the interview
	Expression of thanks
	Expression of commitment to keep the interviewee posted about the finding of the study

Annexure 6: JDDP with main suppliers

CONFIDENTIAL

Annexure 7: Inventory Taking

CONFIDENTIAL

Annexure 8: Library of solutions/ TCUA

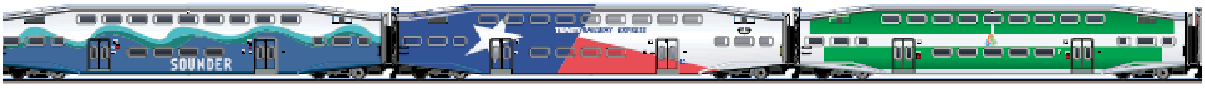
CONFIDENTIAL

Annexure 9: DSM applied at BT

CONFIDENTIAL

Annexure 10: *BiLevel* platform introduction

The BiLevel commuter car is the low-risk, high-performance solution for both established and new-start North American transportation authorities*



Why buy the industry standard BiLevel car?

- *Shortest lead times in the industry: from order to revenue service in less than 12 months*
- *Proven, design meets latest regulations and safety standards*
- *Highly satisfied passengers*
- *Maximum revenues from the highest capacity and best passenger flow of any commuter car*
- *Low maintenance cost and excellent life cycle value*
- *Freedom to choose your own configuration from a variety of attractive options*
- *High flexibility of operation with push-pull capability and efficient train consists.*
- *Compatible with all conventional locomotives for commuter and regional operation*
- *The standard, chosen by more transportation authorities than any other design resulting in the most extensive network of parts and experience*
- *Meets or exceeds all applicable Americans with Disabilities Act (ADA) requirements*
- *Backed by Bombardier's extensive customer services and support network*

Any way you look at it, the Bombardier* BiLevel commuter car sets the standard for commuter rail passenger cars in North America. Each new generation of this car is an evolutionary blend of proven technology, customer input, innovation and inspiration engineered to provide decades of customer satisfaction and operating efficiency.

BiLevel commuter cars for Trinity Railway Express, Southern California Regional Rail Authority, West Coast Express, Sound Transit and Altamont Commuter Express in the Bombardier Plant

Full Compliance

The BiLevel commuter car equipment is Federal Railroad Administration (**FRA**) **Tier 1** compliant and each manufacturing cycle includes complete testing, inspection and documentation stages. The BiLevel commuter cars incorporate all the latest **FRA** regulations and meet all the recently issued standards of the American Public Transportation Association (**APTA**) Passenger Rail Equipment Safety Standards (**PRESS**). Compliance has been demonstrated by rigorous carbody test and inspections by independent third party experts.

Wheelchair accessibility with a 100% reliable, lightweight, conductor-positioned ramp

stan•dard (stan′dẽrd)[1]

noun. something set up and established as rule for the measure of value or quality

adj. having recognized and permanent value

1. 1999 Merriam-Webster

Annexure 11: *TRAXX* platform introduction

EUROPE

THE BOMBARDIER TRAXX
Locomotive Platform

The *BOMBARDIER* TRAXX locomotive platform incorporates electric and diesel-electric locomotives for freight and passenger services based on the Class 185 platform concept.**

It consists of the following types:
- AC locomotives (alternating current)
- MS locomotives (multi-system)
- DC locomotives (direct current)
- DE locomotives (diesel-electric)

The *TRAXX* locomotives cover all types of railway applications in Europe. They operate on all UIC standard gauge railways and in cross-border freight and passenger services. Standardization and modularization enable a high degree of system and component commonality. All *TRAXX* locomotives feature a great number of identical elements, e.g. vehicle dimensions, machine room concept, brake equipment, bogies, traction motors and drive systems, signaling and communication systems, control and diagnostic systems, as well as driver's cab. The operators benefit from significant savings in operations and maintenance through low life-cycle costs, high operational availability and the service-friendly design of our *TRAXX* locomotives.

GPS tracking, GSM remote diagnostics and video cameras for monitoring the train in operation are key components of the communication systems. Prepared for the European Train Control System (ETCS), the *TRAXX* locomotives are ready today for the trans-European traffic needs of tomorrow.

To date, more than 1600 *TRAXX* locomotives have been ordered; more than 1400 operate throughout Europe today, hauling freight and passenger trains on a daily basis, many of them in cross-border services on the North-South and East-West Freight Freeways.

Annexure 12: *Flexity2* platform introduction

‹ Our Creative Spirit, Your Distinctive Look ›

At Bombardier we have transformed the light rail experience through defining designs for urban environments. *FLEXITY* 2 trams will help shape your city's identity.

This new tram's unique design concept – creative customization based on standardized components – allows you to choose a distinctive look that reflects the essential character of your city.

Helping to shape your city's identity

Annexure 13: *Aventra* platform introduction

‹AVENTRA›

Today's passengers and rail operators deserve the best train technology the industry can offer. The *BOMBARDIER* AVENTRA Electrical Multiple Unit demonstrates proven innovation by combining the latest technology with the best-performing solutions from our global portfolio of 22 different metro, commuter and regional train products within one train.**

The *AVENTRA* EMU is the result of an intensive three-year development project to create a step change in train technology meeting the UK market requirements for an innovative, high performance next generation commuter train.

Technology used on *AVENTRA* trains delivers a net energy saving of up to 50% when compared with existing EMUs operating in the UK. This is achieved through a reduction in vehicle weight, the introduction of the lightweight *BOMBARDIER* FLEXX** Eco bogie and a fully welded aluminum carbody.

The *AVENTRA* train offers regenerative braking, high efficiency transformers and traction motors, LED lighting, self-adjusting intelligent air-conditioning and the *BOMBARDIER* EBI** Drive 50 Driver Assistance system. Bombardier's proven *ORBIFLO** wayside control system provides real-time operational information. *AVENTRA* trains feature a further new evolution to this system which allows trains to be remotely switched on and off, thus reducing time needed for train preparation.

Using all of the experience we have gained as the world's largest train manufacturer and maintainer, we have developed the *ORBITA* predictive maintenance system, which allows continuous optimisation of ongoing servicing schedules and spare parts stocks, minimising cost and asset downtime.

Key features

- 21% reduction in train mass compared with best in class
- 70% reliability improvements
- Extensive benefits regarding life cycle cost
- Smart stabling reduces amount of time needed to prepare train for service
- Substantial net energy saving
- Designed for ease of maintenance and maintainability
- Efficient air-conditioning