IDE 409

Ontwerptheorie en -methodologie

Reader

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Voorwoord

Deze reader is samengesteld ten behoeve van het vak IDE409 Ontwerptheorie en -methodologie (OTM). De reader vormt een aanvulling op het boek *Produktontwerpen: Structuur en methoden* van N.F.M Roozenburg en J. Eekels.

In de ontwerpoefeningen IDE100 en IDE202 en in onder meer het vak IDE110 maken studenten al kennis met enkele modellen van het ontwerproces en de meest gangbare ontwerpmethoden. In een wetenschappelijke opleiding mag echter niet worden volstaan met het doceren van de methoden zonder meer. Een universitair opgeleide IO-er behoort ook een kritisch oordeel hebben *over* methoden. Hij of zij moet een bewuste, beargumenteerde keuze kunnen maken voor de beste aanpak van een ontwerpprobleem en zich andere dan de gangbare benaderingen weten voor te stellen. In het vak IDE409 wordt daartoe dieper op de theoretische en methodologische grondslagen van het ontwerpen ingegaan.

Deze reader bevat enkele teksten die dieper ingaan op de stof van de Hoofdstukken 3, 4 en 5 van het boek *Produktontwerpen*, en enkele teksten waarin vanuit andere invalshoeken naar het ontwerpen wordt gekeken en kritische kanttekeningen bij de traditionele modellen van het ontwerpproces worden geplaatst. Bovendien zijn in deze reader enkele case-studies opgenomen.

Wij hopen dat het bestuderen van deze artikelen zal bijdragen aan het inzicht in de specifieke aard van ontwerpproblemen en ontwerpprocessen en aan het vermogen om ontwerpproblemen op een doelmatige wijze te benaderen.

NR/KD

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1 Inleiding

- Roozenburg, N.F.M., Ontwerpmethodologie: een overzicht. *Industrieel Ontwerpen*, nr. 11, 1987, p. 22-24

Dit artikel is een aanvulling op Hoofdstuk 3 'Ontwerpmethodologie' van het boek *Produktontwerpen*. In dat hoofdstuk wordt uiteengezet wat de begrippen 'methode', 'methodologie' en 'ontwerpmethodologie' inhouden. Het artikel geeft onder meer een antwoord op de vraag waarom we voor het vak IDE409 de naam Ontwerptheorie en -methodologie gekozen hebben. Aan het eind van het artikel worden enkele 'fundamentele problemen' aangestipt, die ontwerpmethodologen hebben bezig gehouden. Elders in het boek en de reader wordt daar meer uitvoerig op ingegaan.

Ontwerpmethodologie: een overzicht

Norbert Roozenburg

Ir N.F.M. Roozenburg is universitair docent bij de Faculteit van het Industrieel Ontwerpen van de TU-Delft. Als lid van de vakgroep Bedrijfskunde van de produktontwikkeling is hij belast met onderwijs en onderzoek op het gebied van ontwerpmethodologie.

Ontwerpmethodologie (OM) is een controversieel onderwerp. Ontwerpers en representanten van het vak industrieel ontwerpen laten bij officiële gelegenheden niet na te wijzen op het belang van systematische aanpak en methodische ontwerpen. Sommigen gaan nog verder en stellen dat juist in zijn specifieke werkwijze de kracht van de industrieel ontwerper ligt. In veel opleidingen voor industrieel ontwerpers is dan ook een ruime plaats voor OM ingeruimd. Het lijkt niet overbodig eens bij OM stil te staan. Is OM een mooi geval van de Kleren van de Keizer, of wel degelijk een waardevol gereedschap voor de industrieel ontwerper?
Norbert Roozenburg zal in een reeks artikelen in dit tijdschrift een overzicht geven van dat deel van OM dat voor produktontwerpers van direct belang is.

werpers onder elkaar zijn vaak een meer
uanceerde, soms zelfs sceptische
ning toegedaan. Het gaat uiteindelijk
om de creativiteit en die is nu eenmaal
of nauwelijks te vangen in systemati-
e procedures.
hoe leg je een opdrachtgever uit dat
thodisch werken loont, zo je dat zelf al
oft: je wordt immers voor het resultaat
aald en niet voor het proces. Trouwens
is methodisch werken eigenlijk? Toch
meer dan het ontwerpproces in de alom
ende fasen afronden en dat alleen helpt
h nauwelijks de werkelijke problemen op te lossen?
De ontwerpmethodologen zelf maken het ook al niet gemakkelijk. Enkele belangrijke figuren van het eerste uur, zoals Christopher Alexander en Christopher Jones hebben publiekelijk het nut van OM betwijfeld. Toch wordt in de praktijk juist het meest op de modellen van de beginperiode (1960-1970) teruggegrepen, terwijl veel van het huidige methodologisch werk ver van de praktijk lijkt af te staan. Is OM niet te speculatief? Al dat denken en discussiëren heeft wel tot een aantal mooie modellen geleid, maar *echt* onderzocht is er niet zoveel, en in de praktijk loopt alles nu eenmaal anders dan je denkt. Bovendien, is de veronderstelling dat er een methode voor het ontwerpen bestaat niet net zo'n grote misvatting als het idee van een gemeenschappelijke methode voor het wetenschappelijk onderzoek? *'Anything goes'*, niet alleen in de wetenschap zoals Feyerabend in *'Against Method' beweert, maar ook bij het ontwerpen.*

Wat is ontwerpmethodologie?

Veel ontwerpers zien OM als een losbladig systeem waarin op elk blad een manier te vinden is om een onderdeel van het ontwerpen uit te voeren. Al doorbladerend ontdekken zij dat de klapper nogal onevenwichtig is samengesteld. Sommige taken zijn uitvoerig gedocumenteerd, andere daarentegen geheel niet. Bovendien blijkt een groot deel van de klapper gewijd te zijn aan zaken die niet direct met het ontwerpen zelf te maken hebben. Teleurgesteld wordt de klapper terzijde gelegd en de samenstellers wordt soms een niet ingeloste belofte verweten.

OM is *niet* de verzameling van methoden, hoewel beide alles met elkaar te maken hebben. OM is de wetenschap *van* de methoden. Natuurlijk construeren methodologen wel eens nieuwe methoden, maar hun belangrijkste bezigheid is methoden die zich in de praktijk ontwikkelen, kritisch te bestuderen en te evalueren. Wat *is* een methode, wat voor een type wetenschap is OM en over welke problemen gaat het?

Methode

Of een methodoloog een werkwijze al dan niet een methode noemt, hangt af van het abstractieniveau van de beschrijving. Zonder een flinke mate van abstractie zijn geen algemeen geldende methoden te vinden. Je kunt nooit over *de* methode voor het ontwerpproces spreken, want de keuze van abstractieniveau is nogal arbitrair en hangt sterk af van het gebruiksdoel van de methode. In OM gaat het dus niet om opdrachten of recepten voor een specifieke taak, maar om systemen van regels en structuren van processen die gelden voor klassen van verwante handelingen.

Een methode ontstaat door kenmerkende delen van een proces te onderscheiden en relaties in de tijd daartussen aan te geven. In de methodologie gaat het dus om *wat* er moet gebeuren en *wanneer*. De vraag *'wie doet wat?'* is strikt genomen geen methodologische, maar een organisatorische vraag. Auteurs van ontwerpmethoden laten helaas vaak in het midden voor wie hun methoden bedoeld zijn: de individuele ontwerper, een interdisciplinair produktontwikkelingsteam, een complete industriële organisatie? Dat leidt nogal eens tot misverstanden, want wat een goede methode is voor één ontwerper, is niet automatisch goed voor een grotere organisatie, en omgekeerd.

Methodologie

Methodologie is de wetenschappelijke studie van methoden. 'Wetenschappelijk' omdat men het oordeel *over* methoden zoveel mogelijk baseert op feiten en logische overwegingen.

Tot nu toe waren de meeste OM studies nogal filosofisch van aard: slechts hier en daar werd het ontwerpproces experimenteel onderzocht. Dit is minder vreemd dan het lijkt, want het gaat uiteindelijk niet om de vraag hoe ontworpen *wordt*, maar hoe ontworpen *moet* worden, en juist dat is niet alleen door middel van experimenten vast te stellen.

OM is vooral een kritische, waarderende, normatieve bezigheid. Maar zonder beschrijving van de werkelijke gang van zaken kan OM het toch niet stellen. De behoefte aan experimenteel verkregen descriptieve inzichten in het ontwerpproces komt de laatste jaren dan ook steeds duidelijker naar voren. De descriptieve en normatieve benadering moeten elkaar aanvullen en zijn trouwens vaak moeilijk te scheiden.

Ontwerpen

Moeilijker dan 'methodologie' is het afbakenen van het begrip 'ontwerpen'. De meeste ontwerpmethodologen doen dat dan ook niet expliciet. Zij gaan ervan uit dat ontwerpen een bewust denkproces is dat een rol speelt in *alle* vormen van bewust handelen. Bovendien wordt vaak verondersteld dat datgene wat ontworpen wordt maar weinig invloed heeft op de structuur van het ontwerpproces. Dat wil zeggen: het ontwerpen van produkten, gebouwen, beleidsvoorstellen, en zelfs computerprogramma's zou in grote lijnen op dezelfde wijze verlopen en moeten verlopen. Gezien het tamelijk hoge abstractieniveau van de huidige modellen van ontwerpprocessen valt met dit uitgangspunt nog wel te leven. Maar er zijn natuurlijk verschillen en het is aannemelijk dat deze bij verder onderzoek tot verschillen in methoden zullen leiden. Zo zijn er bijvoorbeeld verschillen in representatiemogelijkheden, die samenhangen met de theoretische stand van zaken binnen een discipline. Ontwerpers van computerprogramma's kunnen hun problemen *en* oplossingen beschrijven in dezelfde (en sterk geformaliseerde) taal. Een produktontwerper of architect kan dat niet. Zij hebben het heel wat moeilijker bij het 'bewijzen' dat hun oplossing *de* (gezochte) oplossing is. Overigens hield Eekels onlangs een pleidooi om OM niet te beperken tot het produktontwerpen alleen, omdat onder het industrieel ontwerpen nog veel meer zaken vallen die ontworpen moeten worden, zoals het fabricageproces, de fabriek en bedrijfskundige objecten als het beleid, het strategisch plan, de ontwikkelingsorganisatie etc. *(Ontwerpmethodologie: mogelijkheden en grenzen, DUP, 1987).*

Methodologie of ontwerptheorie?

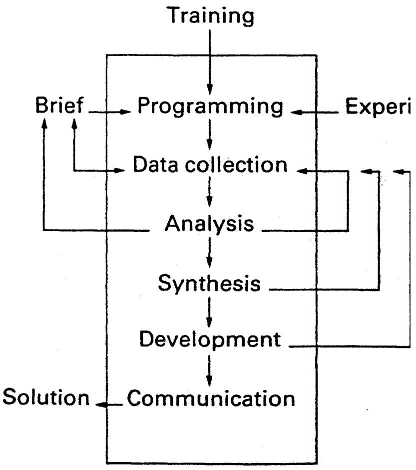
De methodologie van het wetenschappelijk onderzoek heeft een heel wat eerbiedwaardiger verleden dan OM. Het is dan ook niet vreemd dat methodologie-handboeken vrijwel uitsluitend over onderzoek gaan. Is OM als apart vakgebied eigenlijk wel nodig? Immers, wetenschap en techniek, onderzoek en ontwerpen zijn tegenwoordig zo nauw verweven, dat ze nauwelijks meer uit elkaar te houden zijn. Toch moet dat. Het ontwerpen is een anders gerichte activiteit dan onderzoeken. Bij ontwerpen gebruik je kennis om iets ten goede te veranderen in je omgeving, bij experimenteel onderzoek dwing je veranderingen in een deel van de omgeving af om de kennis erover te vergroten. Beide processen kennen vergelijkbare elementen, maar ze zijn anders geschakeld. Dat brengt methodische verschillen met zich mee en daarom is OM nodig.

Het is niet zo dat onderzoekmethodologie *niets* te bieden heeft voor ontwerpers. Allereerst omdat in ontwerpprocessen wetenschappelijke kennis overal een belangrijke rol speelt. Om die kennis goed te gebruiken is bekendheid met onderzoekmethodologie geen overbodige luxe.

Daarnaast is het zo dat activiteiten, bedoeld als ontwerpproces, heel gemakkelijk kunnen omklappen tot een vorm van onderzoek, bijvoorbeeld als je iets ontwerpt op basis van een theorie, daarvan een werkend model maakt en dan ontdekt dat het niet werkt, omdat de theorie niet deugt. Je leert dan – onbedoeld – iets over de theorie en deed eigenlijk een wetenschappelijk experiment, mits één en ander methodologis
verantwoord was opgezet.

Ten slotte: OM en onderzoekmethodol
gaan *beide* over methoden. Uit de ontwi
ling van de onderzoekmethodologie zij
enkele lessen te leren voor ontwerpme
dologen. De eerste is dat het niet vruch
is *uitsluitend* methoden te bestuderen.
grens tussen onderzoekmethodologie e
andere takken van de wetenschapsfilos
blijkt niet scherp te trekken. Automatisc
komt men terecht bij problemen rond d
aard van wetenschappelijke kennis, de
logica, de ethiek en dergelijke. Ook voo
OM is dit te verwachten. Het *'hoe'* hang
eenmaal samen met het *'wat'*. Het verb
ren van ontwerpmethoden vraagt om e
diepere analyse van de aard en de struc
van ontwerpproblemen.

De tweede les is dat de filosofische ben
ring *alleen* onvoldoende inzicht geeft in
verschijnsel wetenschap. In de modern
wetenschapsfilosofie wordt dan ook alg
meen erkend dat vakwetenschappelijke
benaderingen, zoals de historische en
vooral de sociaal-psychologische, een
belangrijke rol kunnen en moeten spele
Ik meen dat dit ook voor de studie van h
ontwerpen zo is. De puur methodologis
benadering zou moeten worden aangev
met historische studies van ontwerpen
uitvinden, onderzoek van de sociale str
ren waarin ontworpen wordt en psycho
sche studies van de eigenschappen var
ontwerpers. Om de integratie van derg
studies aan te duiden zouden de begrip
'Ontwerptheorie' of *'Ontwerpleer'* bete
hun plaats zijn dan OM.



**Archer's bekende 'Basic desig
procedure'. Het topje van de ijsl
de 'Systematic Method' omvat
tientallen activiteiten plus een
relatiediagram.**

Fasenmodellen

Archer's *'Systematic Method For De
ners' (Design, 1963-4)* is waarschijnlijk
bekendste voorbeeld van de eerste resu
ten van OM, maar ook in andere discipl
zijn voorbeelden van dergelijke fasenmo
len te vinden, zoals het Duitse VDI-2222

odel voor werktuigbouwkundig ontwer- n en het Engelse RIBA Plan of Work voor architect.

et deze modellen beoogden de ontwerp- ethodologen een rationele structurering n het ontwerpen; intuïtie en creativiteit uden binnen het geboden systematische der optimaal tot hun recht komen. Dit type odel is nogal normatief en daartegen ordt vaak bezwaar gemaakt. Zo is er de itiek dat de stringente scheiding tussen alyse en synthese – die meestal voorge- hreven wordt – niet erg realistisch en elmatig is. Die kritiek is juist en onjuist.

j die deze modellen zien als een psycholo- sch model voor het denken van één twerper, hebben ongetwijfeld gelijk.

e fasenmodellen zijn echter vooral bedoeld or het structureren en plannen van het erk van een team van ontwerpers en dere specialisten. In dat geval ontkomt en niet aan het – desnoods wat kunst- atig – faseren van het project, omdat ders het verdelen en afstemmen van ken, het plannen en budgetteren, tussen- dse evaluaties en voortgangscontrole niet ogelijk zijn.

iervoor vormen de fasenmodellen een terst nuttige basis en het is niet vreemd dat j het meest toegepaste gereedschap van OM zijn.

ethodiek

Een tweede belangrijk thema van OM is methodiek, dat wil zeggen: de methoden technieken zelf. Aanvankelijk bestond het erk vooral uit het inventariseren en classifi- ren van methoden, veelal ontleend aan dere disciplines zoals management, esliskunde en psychologie.

ones' *'Design Methods: Seeds of human itures' (John Wiley & Sons, 1970)* is het este voorbeeld van deze benadering. Zijn oek bestrijkt het gehele ontwerpproces, aar er zijn ook methodenoverzichten die ch tot enkele aspecten van het ontwerpen eperken zoals Rickards' *'Problemsolving rough creative analysis' (Gower Press, 974).* Uiteraard bevatten dergelijke studies teeds een systematische indeling die de euze en toepassing van technieken moet ereenvoudigen. Tot op zekere hoogte is 'n indeling arbitrair. Het is met ontwerp- chnieken als met gereedschap: je kunt er ltijd iets mee doen wat zinvol is, maar igenlijk niet bedoeld was. Zo is brainstor- ning een creativiteitstechniek, maar ook itstekend geschikt om snel de in een groep anwezige kennis over een probleem te ergaren.

eel technieken blijken een problematische erst stap te bevatten, waarin het op erva- ing, inzicht en overzicht van de ontwerper ankomt en waarbij de techniek zelf nauwe- jks helpt. Een voorbeeld is het kiezen van arameters bij de morfologische methode. ok hier geldt, zoals bij alle gereedschap: et resultaat is zo goed als de gebruiker, wat atuurlijk niet wil zeggen dat het gereed- chap zelf géén invloed op het resultaat eeft.

undamentele problemen

Rond 1970 verminderde de belangstelling oor fasenmodellen en methodiek.

e resultaten van OM vielen tegen, zeker in et licht van de toen hooggespannen erwachtingen. Tot dan toe was OM sterk eïnspireerd door operations research, besliskunde, problemsolving en onderzoekmethodologie. Men ging zich realiseren dat ontwerpproblemen in veel opzichten anders zijn dan de problemen van die disciplines. Een ontwerpprobleem is géén onderzoekprobleem en meer dan een keuze- of optimaliseringsprobleem.

Door teveel te kijken naar de methodologieën van andere disciplines waren de eigen problemen van het ontwerpen uit het zicht geraakt, zo werd terecht geconstateerd.

Wat is ontwerpen eigenlijk, waarin verschilt het van andere vormen van denken en doen en wat zijn daarvan de methodische consequenties? Het onderzoek wordt nu fundamenteler en het veld van studie breder. Ik kan slechts enkele onderwerpen noemen. Ontwerpproblemen worden benaderd als *ill-defined problems.* Dat zijn problemen waarvoor niet duidelijk is vast te stellen dat de oplossing gevonden is, omdat de probleemstelling zelf als het ware mee ontworpen wordt. Dergelijke problemen vragen om een andere aanpak dan de nogal lineaire *'systems-engineering approach'.*

Veel aandacht krijgt de logische structuur van het ontwerpen. Onder meer Eekels en March tonen aan dat het denken en redeneren bij het ontwerpen door eigen patronen worden gekenmerkt die niet tot deductie en inductie zijn te herleiden (zie *Industriële Doelontwikkeling* en *The Architecture of Form, Cambridge University Press, 1976).*

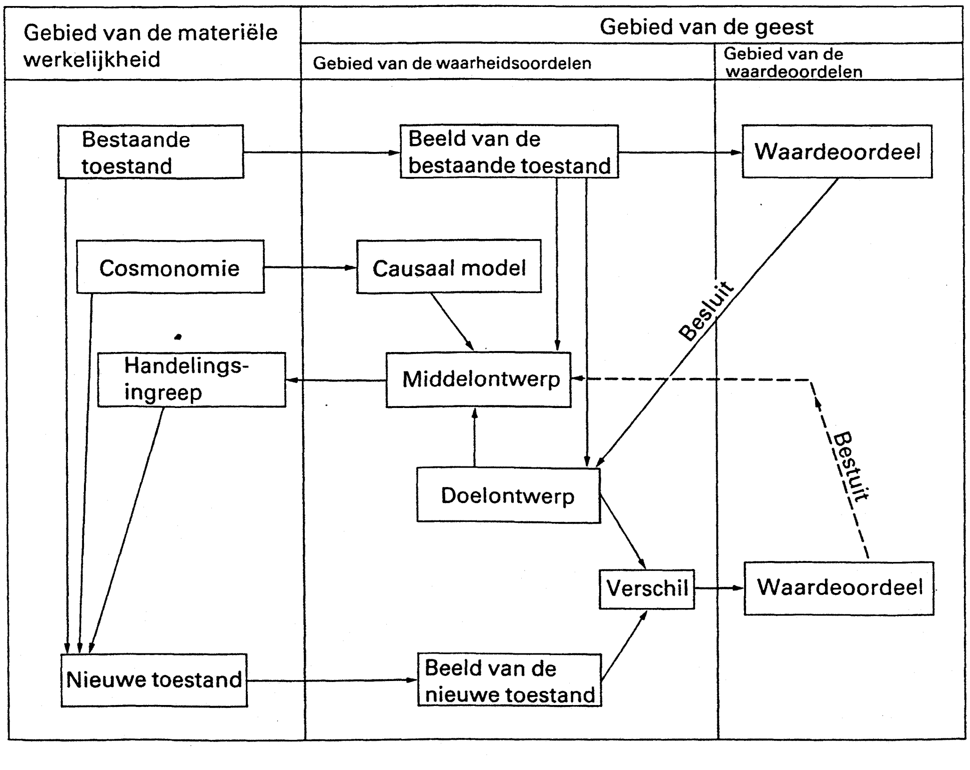
Studies op wetenschapsfilosofisch terrein leiden tot het inzicht dat ook bij de wetenschappelijke theorievorming à priori kennis, intuïtie en ideeën een onmisbare constructieve rol spelen; het is dus helemaal niet nodig dergelijke zaken buiten de deur te houden om wetenschappelijk te werken, zoals in de beginperiode van OM wel eens werd gedacht.

Weer andere studies gaan over de functies van kennis bij het ontwerpen en over de vraag of er een *'designerly way of knowing'* bestaat – zoals Archer poneerde – als tegenhanger van de nogal verbale wetenschappelijke kenwijze.

Als laatste noem ik Eekels' *'Structuuranalyse van het handelen en maken'.* Zijn schema's maken inzichtelijk hoe denken en doen, modellen en werkelijkheid, doelen en middelen, feiten en waarden op elkaar ingrijpen bij het ontwikkelen, realiseren en gebruiken van produkten. Zij zijn een krachtig hulpmiddel om mogelijke oorzaken van methodische problemen tijdens een project te onderkennen (zie *Industriële Doelontwikkeling, Van Gorkum & Comp, 1973).*

In vergelijking met de periode 1960-1970 ligt het zwaartepunt niet meer bij normatieve systematische methoden als zodanig, maar bij wat daaraan ten grondslag ligt. OM streeft nu naar groter inzicht in de aard en moeilijkheden van het ontwerpen, zodat ontwerpers beter in staat zullen zijn *zelf* hun ontwerpproces te structureren, rekening houdend met eigen stijl en mogelijkheden *en* de specifieke situatie waarin ontworpen wordt.

Dat is, lijkt mij, een zinvolle doelstelling om na te streven. ◁



Eekels' 'Structuur van de handeling'. Dit is het schema voor de handeling in het algemeen. Het boek 'Industriële Doelontwikkeling' bevat nadere uitwerkingen.

2 Prescriptieve modellen van het ontwerpproces

- VDI Guidelines 2221, Systematic Approach to the Design of Technical Systems and Products. VDI-Verlag, 1987.

- Cross, N. and N.F.M. Roozenburg, Modelling the Design Process in Engineering and in Architecture. *Journal of Engineering Design*, vol. 3, no. 4, 1992.

De twee teksten van dit deel van de reader vormen een aanvulling op Hoofdstuk 5 'De structuur van het ontwerpproces' van het boek *Produktontwerpen.*

De *VDI Richtlijn 2221* is een heel karakteristiek voorbeeld van een prescriptieve ontwerpmethodiek. De richtlijn is de neerslag van de ideeën over 'systematisch ontwerpen' in de werktuigbouwkunde die in de afgelopen decennia zijn ontstaan. Duitse en Oost Europese werktuigbouwkundig ingenieurs hebben daaraan een grote bijdrage geleverd, maar in de richtlijn zijn ook duidelijk Angelsaksische invloeden te bespeuren. Voor wat betreft de opzet is VDI 2221 vergelijkbaar met Hoofdstuk 5 van het boek, maar de richtlijn gaat dieper in op de verschillende fasen en activiteiten. Bovendien bevat de richtlijn voorbeelden van systematisch ontwerpen op het gebied van mechanische systemen, fabricageprocessen, mechatronica en software. Daarmee heeft men willen aantonen dat de systematische benadering van VDI 2221 algemeen toepasbaar is voor het ontwerpen van technische systemen en producten. Maar is dat ook zo?

In het artikel *Modelling the Design Process* vergelijken Cross & de modellen van werktuigbouwkundig ontwerpen en architectonisch ontwerpen. Zij vragen zich af waarin en waardoor deze modellen verschillen en pleiten voor een (hernieuwde) 'integratie' van het typisch werktuigbouwkundige en het typisch architectonisch model.

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VDI GUIDELINES

August 1987

VEREIN
DEUTSCHER
INGENIEURE

Systematic Approach to the Design of Technical Systems and Products

VDI 2221

Translation of the German edition 11/1986

The German edition of this Guideline and not the English translation shall be taken as the authoritative Guideline.

Contents

VDI Society for Product Development, Design and Marketing
Committee for Systematic Design

Preliminary Note

The VDI Society for Product Development, Design and Marketing (VDI-GKE) published Guideline VDI 2222, "Systematic Approach to Design – Conceptual Design of Technical Products", in 1977. That Guideline examined the most important fundamental principles for a systematic approach to design and it received national and international recognition from both engineering design practitioners and educators.

Acknowledgements

The chairman and members of the Committee responsible for this Guideline hope that the aims set out in Section 1 have been achieved and that a basic working document on engineering design has been produced which can be used in all branches of industry. The general approach to the design of technical products described in this Guideline is fully supported by the VDI-Society for Product Development, Design and Marketing (VDI-EKV).

The chairman of the Committee was Prof. Dr.-Ing. *W. Beitz*, Berlin, and the members were:

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Dipl.-Ing. *Th. Derhake*, Braunschweig
Prof. Dr.-Ing. *H.O. Derndinger*, Stuttgart
Prof. Dr.-Ing. *K. Ehrlenspiel*, München
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Dipl.-Ing. *P. Selbmann*, from VDI-Headquarters, was responsible for all administrative matters. The English edition of the Guideline was edited by *K.M. Wallace* CEng, Cambridge. The work of all those involved is gratefully acknowledged.

VEREIN DEUTSCHER INGENIEURE

1 Aims

The competitive manufacture of technical systems and products is influenced decisively by the effectiveness of the design process. This process is characterised by a wide variety of tasks which must be carried out under conditions specific to each company and under conditions imposed by market trends and technical developments. A *systematic approach to the design of technical systems and products* which is to be generally applicable in practice must take account of this wide variety. It is intended to achieve this aim by structuring the most important relationships, and the working methods deduced from them, with the aid of several VDI Guidelines.

Guideline VDI 2221 deals with the generally valid principles of design independently of a specific branch of industry. It defines those design stages and results which, because of their logical nature and usefulness, provide a general approach in practice. The most important methodological principles which provide the basis for the solution of problems are those of the systems approach [101, 102]. Also included are the familiar design methods recommended principally for mechanical and precision engineering [17, 18, 20, 23, 25]. In this Guideline, the examples of the general approach applied in various branches of industry are intended to indicate special relationships and ideas, though the differences between branches are becoming less marked due to the influence of multidisciplinary design teams. In addition, the examples are also intended to provide assistance when reassessing and improving the existing design approach within an organisation, with the objectives of: reducing the expense and effort involved; making the optimum use of computers; and ensuring the marketability of the products designed. In order to achieve uniform data processing within a company, it is important to integrate the use of computers within a systematic approach to design. This Guideline has therefore been produced with particular reference to the application of computers in design.

An additional aim is to summarise and order the wide variety of design methods which have arisen in recent years as a result of work carried out in research and practice. This should enable the reader to recognise their typical applications without the need for detailed descriptions.

The terms required for a general approach are also defined. This is both to facilitate understanding this Guideline and to unify the meaning of the terms in research and practice.

Based on this *Overall Guideline* further detailed Guidelines are to be produced. These will describe, with the help of examples, topics such as the individual design phases, for example conceptual design and embodiment design, and also particular design procedures in different branches of industry, for example mechanical engineering and precision engineering. This will make it possible to cover in much greater detail the particular requirements and methods of individual design stages and of different specialist areas. It will also permit the ideas of the different *schools of design methodology* to be taken into account.

Producing these detailed Guidelines does not bring into question the overall aim of creating a generally applicable approach to design. Instead, it is hoped that by describing special relationships and applications the validity of the overall approach and the possibility of applying general methods in specific cases will become clearer.

2 Fundamentals of the Systematic Approach

A multitude of different problems need to be solved in the course of design. It is thus natural to transfer the approach utilised in the process of solving general problems to the process of design.

The *process of solving problems* represents a permanent relationship between goals, planning, execution and control, linked by decisions. *Systems engineering*, as an interdisciplinary methodology for solving problems associated with artificial systems, provides a general description of this process [101, 102]. *The model of the systems approach* shown in Fig. 2.1 divides the development of a system into *life phases*, progressing from the abstract to the concrete. The model also contains a strategy for solving problems which is, in principle, applicable to every life phase.

Problem Analysis: Every problem or task initially has the effect of confronting the solver with something which is more or less unknown in terms of the solution to the problem. The scope and extent of this confrontation depend on the level of knowledge and information at the disposal of the solver. It will frequently be necessary to obtain more information about the problem, thus discovering further requirements of the task, details of the constraints and possible methods of solution.

Problem Definition: Subsequent definition and precise formulation of the problem to be solved, based on a more detailed level of information, facilitate the search for a solution. This is because the essence of the task and the requirements to be met are expressed in the language of the problem solver, without a specific solution in mind.

System Synthesis: In the course of searching for solutions during this particularly creative phase of the

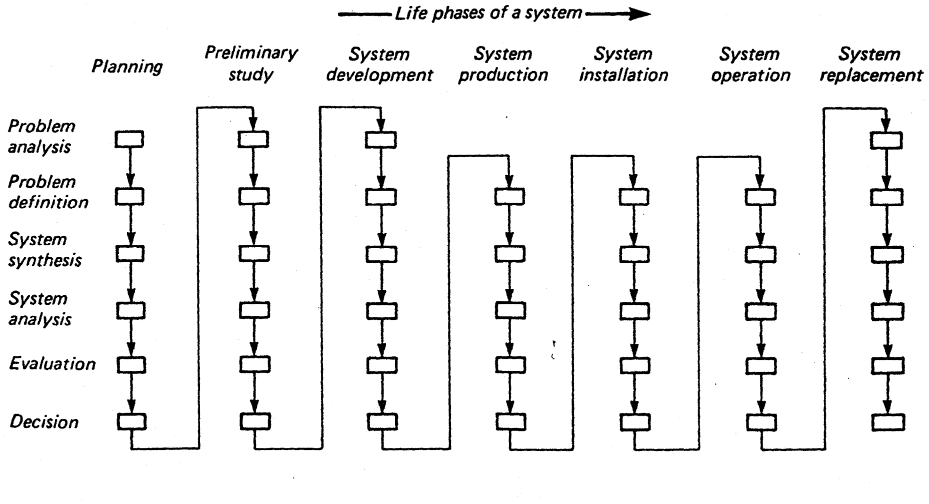


Fig. 2.1. Model of the systems approach, after [102, 104]

process, ideas or even concrete solutions are developed and combined. A most important feature is the development of, or recognition of, a number of different solutions.

System Analysis: In this step the proposed solutions are analysed in order to gain the information necessary to reach a decision.

Evaluation and Decision: An evaluation of the characteristics of the proposed solutions against the specified requirements is essential in order to arrive at a decision about whether to develop the preferred solution for the system further or to stop the development altogether.

Not until these steps are appropriately combined may we refer to a strategy of plan or approach. The simplified representation in Fig. 2.1 of a linear linking together of the steps is not sufficient to reach a solution in the case of complex problems. It is important and customary to make use of repeated cycles in which the different steps are processed several times. This iterative procedure, shown in Fig. 2.2, leads to an increase in the level of information for a step being repeated, and corresponds to a learning process.

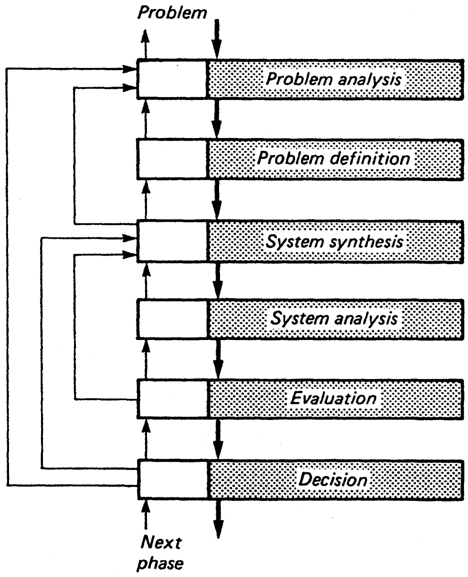


Fig. 2.2. Cycles in the systems approach to problem solving

The procedural steps contain individually and in their entirety the activities of collecting, processing and transmitting information. In such *information conversion*, the output of information from one step results in a gain of information, either for the next procedural step or for the preceding one. The collecting and processing of information are also essential for synthesis and analysis, which are always closely linked and interdependent.

A breakdown of the problem-solving process into parallel paths is recognised by cybernetics as being an effective and economical strategy for solving complex problems. This strategy has proved effective in practice, and consists of subdividing a complex overall problem into defined sub-problems at as early a stage as possible. In this way, solutions can be found more easily. The sub-solutions are then combined into an overall solution.

This important strategy is shown in Fig. 2.3, which also illustrates the fundamental systematic approach of structuring a system into sub-systems and system elements. Such a structuring promotes: the recognition of sub-problems by revealing patterns and relationships; the discipline to proceed systematically; the development of alternative solutions; the adoption of familiar and well-tried sub-solutions; and the introduction of a rationally organised division of labour. All the aforementioned also provide the basis for the application of computers in design.

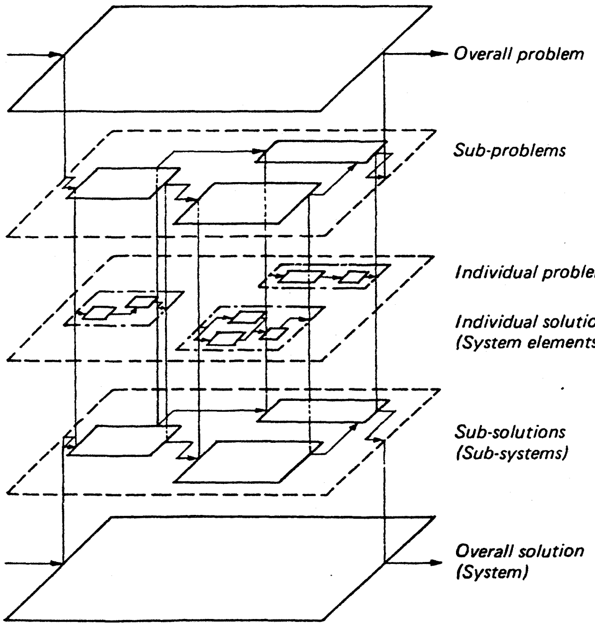


Fig. 2.3. Method of structuring problems and systems

A further, generally valid and established approach to solving problems is to proceed through several phases in increasingly concrete terms — the strategy being: *from the abstract or general to the concrete or specific*. Thus, for example, fundamental relationships are first determined in principle, and embodiment details not established until later. The following strategy proceeds in the same direction: *from the most important to the less important, or from the main problems to the sub-problems.*

Findings of the psychology of thinking [103], based on behavioural research, indicate that such strategies, and procedures based on them, should not necessarily be pursued in a strictly linear fashion. Human thinking is typically characterised by alternating between the abstract and the concrete, between concentrating on the whole and on the individual elements. It is therefore important for a plan of approach to include iteration, the repetition of phases or steps, with those of little importance being passed over rapidly or even skipped.

Particularly in problems of *Industrial Design,* where external appearance is critically important, it is necessary to view the problem as a whole at the outset and attempt an overall solution before progressing to a division into sub-problems. In this case, the overall appearance of the solution takes priority over the individual elements of which it is composed, and the approach is to design from the "outside" to the "inside", rather than vice versa which is the more usual approach. Further examples of this approach are tasks involving ergonomics, which are oriented towards human perception, for example visually, acoustically or by taste. This approach to design is common in architecture and consumer products.

The Industrial Design and the systematic approaches should not be viewed as opposites. Both approaches should be used where appropriate during the development of a technical system. Thus, for example, in the case of a consumer product where the emphasis is on customer appeal, the preliminary design for its external appearance will be carried out before its function-oriented design. Using this approach, it is often possible to identify important requirements missing from the preliminary definition of the problem.

3 Plan of Approach

A general plan of approach must be applicable to the whole range of technical tasks. For this reason, these tasks will first be characterised in order to provide a basis for the structure of the approach recommended.

3.1 Tasks of Design

The wide variety of tasks is determined in the first instance by their *origin.* An important distinction must be made here between requests from the product planning department within a specific company, requests from customers on the basis of a fixed specification, and in-house requests for production and test equipment, that is there are external and internal sources of requests.

The second determining characteristic is the *type of production.* It is obvious that products and product ranges manufactured by batch or mass production require a different organisational structure and a different emphasis in design than products manufactured singly.

The third determining characteristic is the *degree of novelty.* This differentiates on the basis of completely new designs, further developments of existing designs and adaptive designs. The degree of novelty of a design task can either refer to the overall product to be developed or merely to individual assemblies, and determines to a considerable extent the design steps required, the aids employed and also the organisational structure needed.

The design process must be adapted to each particular branch of industry, since the demands made on products in different branches vary. In precision engineering, for example, the goals of miniaturisation and functional quality lead to an increased use of microelectronics; in heavy engineering aspects of safety are generally in the foreground; in machine tool construction, the emphasis is on working accuracy, speed and flexibility; and the motor industry pays particular attention to safety, appearance, ergonomics and costs. Chemical process engineering, which is frequently concerned with large-scale plant and equipment, places heavy demands on safety, reliability, and operational efficiency to ensure the necessary consistent high quality and low production costs of the chemical products.

In accordance with the different demands made on the products to be developed, the following design goals generally need to be fulfilled: optimisation of function; minimisation of costs; conformity with extreme conditions, for example with respect to performance, weight and precision; and appropriate ergonomics, including a characteristic and appealing appearance. Depending on their relative weighting, each of these goals should be paid appropriate attention and one goal should not dominate the whole design approach.

The sequence of the design process is not only determined by the demands made on the product itself, but also by general requirements and constraints, both external and internal to the company. These include:

- *Competitive Situation*: This leads to product developments having to be undertaken more frequently and quickly and increases the necessity for product innovations and diversifications. Computers provide a means of speeding up the design and manufacturing processes (CIM – Computer Integrated Manufacture).
- *Pressure of Costs*: This makes it necessary to continually reduce costs, including both production and operating costs (overall product costs [53]).
- *Pressure of Time*: This makes it necessary to plan carefully the overall design and production processes.
- *Special Requirements*: These are increasing, particularly in the manufacture of one-off products. In the case of plant and products for special purposes, there is a particular need for detailed plans to meet these special demands at favourable cost and within the appropriate timescale. In such cases, modules and standard components, together with existing production and assembly facilities, should be used whenever possible.
- *Variety of Regulations*: The number of regulations has grown considerably, particularly where exports to many countries are involved.
- *Outside Production*: In numerous companies, product development must often take into account the fact that the whole product or individual assemblies must be produced without difficulty by outside or foreign manufacturing plants.
- *Increased Performance and Complexity*: The number of specialist fields of knowledge required for design is increasing continually.
- *Advances in Microelectronics*: Microelectronic solutions are increasingly replacing mechanical ones.
- *Research Findings*: There have been important advances in many classic and modern fields of knowledge, including strength of materials, materials technology, machine elements, machine dynamics, fluid mechanics, production technology and information theory. This makes it necessary for design engineers to continually update their education and training.

3.2 General Approach

The systems approach described in Section 2, together with additional design methods, is used to develop a general approach to design which is applicable to the wide variety of tasks outlined in Section 3.1. Although this Guideline aims to transcend specific branches of industry, the ideas presented in this general approach tend to be more closely associated with mechanical engineering. Reference to the ideas and the terminology of other branches will be made in Section 4, thus indicating the general validity of the approach.

The life phases of a system illustrated in Fig. 2.1 are equally valid for products in mechanical engineering, precision engineering, process engineering and software development. Fig. 3.1 illustrates how the ideas and concepts common in these branches fit the life phases of systems theory. The starting point is provided by requirements and constraints both external (market, customer) and internal to the company. These either define the design task directly, or are developed into a product idea or task definition in a preliminary process of product planning. The product is then defined in more concrete terms during the design process so that it can be realised, for example in the case of mechanical products by the manufacture and assembly of components. The product is subsequently tested before it is delivered to the user by way of sales. In spite of maintenance

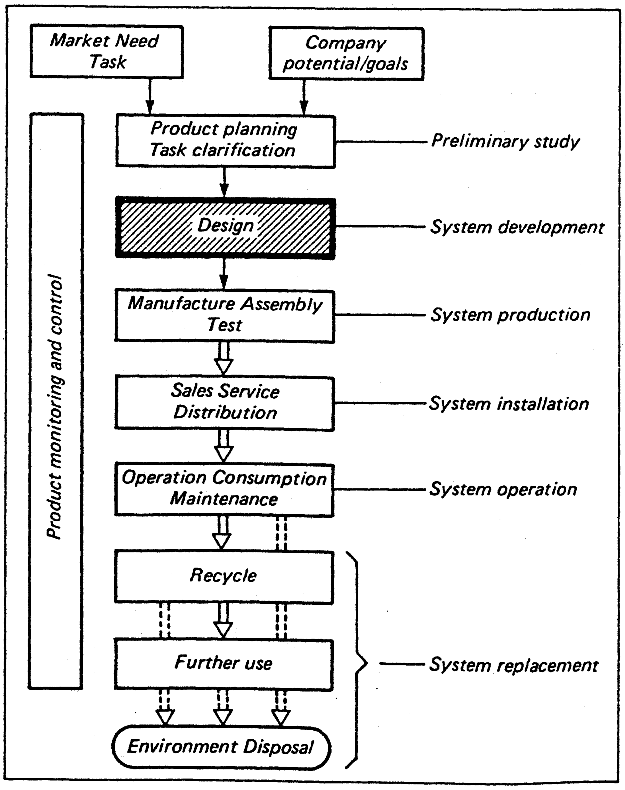


Fig. 3.1. Design within the framework of Guideline VDI 2221 as part of the life phases of a system as shown in Fig. 2.1

measures or subsequent reprocessing for further use, the product life cycle is generally limited. The aim should then be to recycle the old product by putting the materials to further use. This life phase is gaining in importance in order to conserve resources and protect the environment.

Such a sequence occurs for a one-off product, such as heavy-engineering and chemical process plant, generally only once, see Fig. 3.2. In the case of batch and mass produced products in mechanical engineering and precision engineering, it would be too much of a risk for them to be realised directly as a finished product. Here, a first round of planning, design, manufacture and assembly is undertaken to produce a model, which when tested may indicate ways of improving the design. This information is incorporated in a new cycle either to manufacture an improved model for further tests (thin line), or to manufacture a prototype. It may then be worthwhile for still further refinements to be made, before finally putting the finished product into full-scale production.

The design process, as part of product creation, is now subdivided into general working stages, making the design approach transparent, rational and independent of a specific branch of industry, see Fig. 3.3.

The overall approach is divided into seven stages, correspondingly producing seven results. Depending on the task, either all the stages are completed or only some, with stages being repeated as necessary. In practice, individual stages are often combined into design phases, which assists the overall planning of the design process. Such a combination into phases can differ depending on the branch of industry or company, and also according to the concepts involved (see Section 4).

Fig. 3.3 does not include the activities of evaluation and decision which are necessary in all the stages. These determine whether or not it is necessary to repeat preceding stages.

Stage 1 is necessary to clarify and define the *requirements* of the task requested by the customer or the product planning department. It includes: collecting all the information available and discovering where there are gaps; checking and supplementing external requirements; adding specific company requirements; and defining and structuring the task from the point of view of the designer.

The result is a *specification* (requirements list) which can be established independently of any solution. This list of requirements is an important working document which should accompany all subsequent stages, and which should be constantly reviewed and kept up-to-date. Important findings in the course of the design process can lead to existing requirements being modified and new requirements being added. Because the specification is so important, all modifications to it should be undertaken formally and on a regular basis.

Stage 2 consists of determining *functions*, first the *overall function* and then the most important *sub-functions* (main functions) to be fulfilled by the product or system being designed. The classification and combination of these sub-functions into *structures* forms a basis for the search for solutions for the overall product or function.

The result is one or several *function structures*. These are usually presented as formal diagrams but, in some cases, simple descriptions suffice.

In *Stage 3* a search is made for *solution principles* for all sub-functions, or initially for the most impor-

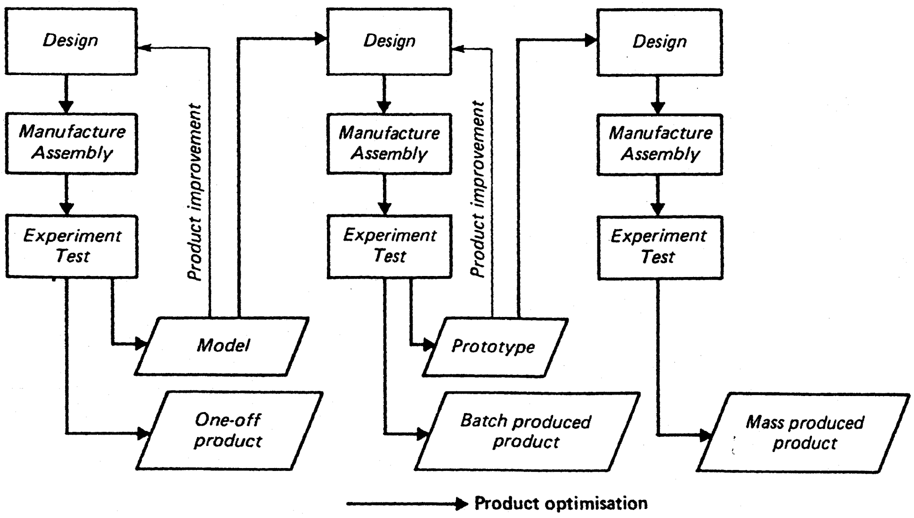


Fig. 3.2. Cycles in product creation

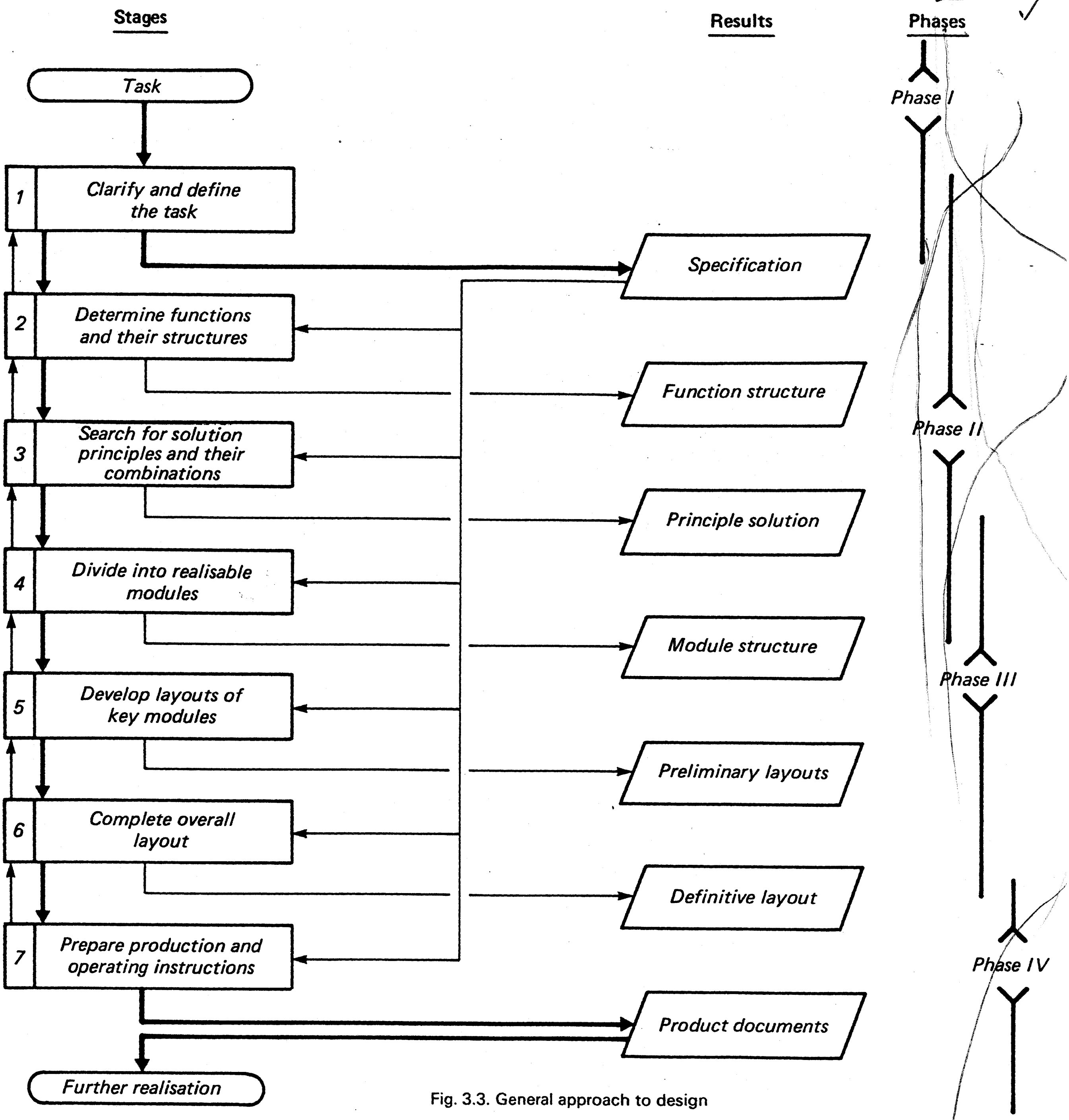


Fig. 3.3. General approach to design

tant sub-functions of the function structure. Physical, chemical and other effects need to be selected for this purpose, and these must be realisable in principle by embodiment features. In the case of mechanical systems, such embodiment features include, for example, the geometry (active geometry), the motion (active motion) and the type of material. The solution principles discovered for sub-functions must subsequently be combined in accordance with the overall function structure. In so doing, further sub-functions (auxiliary functions) may become apparent, and these in turn make possible the realisation of certain effects or solution principles.

The result is a *principle solution* which represents the best combination of physical effects and preliminary embodiment features to fulfil the function structure. It may be documented as a sketch, a diagram, a circuit or even a description.

In *Stage 4*, the principle solution is divided into *realisable modules*, before starting the complex and time-consuming process of defining these modules in more concrete terms.

This results in a *module structure* which, in contrast to the function structure or principle solution, provides a preliminary indication of the breakdown of the solution into the realisable groups and elements (sub-systems and system elements) which, together with their links (interfaces), are essential for its implementation. This can be represented in the form of layout drawings, process flow charts, circuit diagrams or software flow charts. A module structure is particularly important in the case of complex products, as it facilitates the efficient distribution of design effort. It also helps with the identification and solution of embodiment design problems. Thus, for example, a distinction is made between: design modules limited according to working principle; assembly modules, allowing easy assembly; maintenance modules, allowing easy maintenance; recycling modules; and basic and variation modules, allowing a modular product system [105].

Stage 5 consists of developing the layouts of the *key modules*. The level of refinement of the geometry, materials and other details should only be pursued as far as to allow the optimum design to be selected.

The result of this stage is a set of *preliminary layouts* for the key modules, which can be represented as scale drawings, circuit diagrams, etc.

In *Stage 6*, the preliminary layouts of the modules are completed by the addition of further detailed information about the assemblies and components previously not included, and by the combination of all assemblies and components. Often it is possible to define those modules not included in Stage 5 by selecting standard or commercially available items.

This stage results in a *definitive layout* containing all the essential configuration information for the realisation of the product. The main forms of representation are scale layout drawings, preliminary parts lists, instrumentation flow charts, etc. (see Section 4).

In *Stage 7* all the final *production and operating instructions* for which the design department is responsible are prepared. This stage thus overlaps with the preceding one.

The result of this stage is a set of *product documents*, in the form of detail and assembly drawings; parts lists; and production, assembly, testing, transport and operating instructions.

In all the aforementioned stages several solution variants are analysed, and where necessary tested in the form of models or prototypes, and then evaluated. The activities of selecting, optimising and deciding take place in all the stages, but they have not been shown in the general plan of approach. It should be emphasised that the seven stages above can be further subdivided into additional steps, depending on the complexity of the task (see Section 4).

It is important to note that the stages do not necessarily follow rigidly one after the other. They are often carried out iteratively, returning to preceding ones, thus achieving a step-by-step optimisation.

Depending on the degree of novelty and the aim of the task, the stages will assume different levels of importance. It would appear dangerous to skip individual stages completely, because the design process would then no longer be comprehensive, and some of the information necessary for taking decisions could be missing.

For some products, particularly where specialised fields are involved, it is necessary to execute individual stages in parallel. Thus, for example, in the case of large process plant in chemical engineering, the designs of the chemical process, the mechanical system and the structural layout are carried out separately, although naturally in close coordination with each other. Also in the case of precision engineering, the electromechanical assemblies, the electronics and the software can all be designed in parallel.

Fig. 3.4 shows a modification of the general approach for such tasks. According to this figure, it is more appropriate to undertake the stage of clarifying and defining the overall task and the stage of determining the overall functions to be fulfilled, before the subsequent stages are allowed to proceed in parallel. After completing the design in each stream, the individual results are combined into common product documents. This provides a check on the overall compatibility of the individual results.

The structure shown in Fig. 3.4 can naturally only act as an example. It needs to be modified to comply with the specific requirements of the task and of the particular organisation in each case.

The general approach to design may be summarised as follows:

- The approach contains: the definition of requirements and constraints in order to formulate the task to be solved more precisely; the search for and development of solutions; and the selection and optimisation of solution variants.
- When defining requirements and constraints the following are necessary: completeness; accuracy; weighting; independence from specific solutions; and order.
- The search for and development of solutions takes place at different levels of refinement and complexity:
  - Principle solutions (concepts) for the overall function and for individual functions.
  - Preliminary layouts of modules and elements,

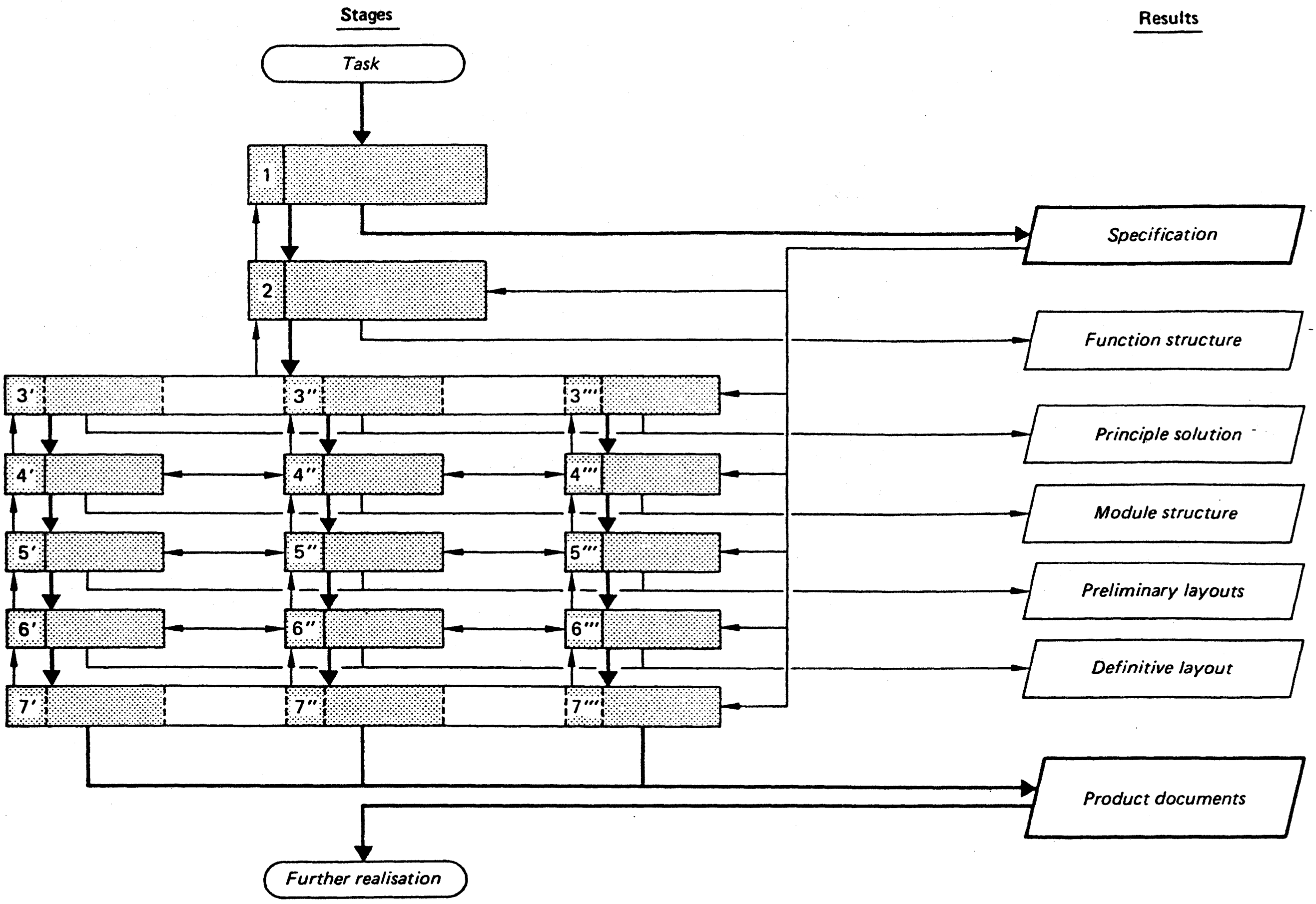


Fig. 3.4. General approach for a project with independent but coordinated sub-projects

individually and combined into groups of a higher order.

- Definitive layouts of all modules and elements.
- Detailed preparation of production and operating instructions.

– The decision on the best overall solution is taken after a comparative evaluation of the extent to which the proposed solution variants meet the requirements in the specification. Through this evaluation the value ratings and shortcomings of proposed solutions can be determined by reference to a defined ideal solution.

4 Examples of the Systematic Approach

In this section, five examples, two from mechanical engineering and three from other branches of industry, are used to demonstrate how the general design approach described in Section 3.2 can be applied to a wide range of design tasks.

4.1 Examples from Mechanical Engineering

Introduction

Mechanical engineering products within the context of this Guideline are those technical systems in which the main conversions are of energy and materials, and which in terms of physical size fall between process engineering plant and precision engineering products. It is not necessary to make further fine distinctions within the field of mechanical engineering as all technical systems can be defined in terms of their function, embodiment, production and operation.

In addition to the optimisation of function, the aim in mechanical engineering is to minimise production costs, for example by means of high material utilisation and modular construction, and to lower running costs, for example by high operating speeds and efficiency. Nowadays, increasing use is being made of electronics, power electronics for drives and microelectronics for controls. The use of electronics has a far-reaching effect on the designer's approach, since it is now necessary to take account of electronic and software solutions in addition to mechanical and electrical solutions. The designer's problems are complicated further by demands for increased safety and better ergonomics and these have fundamentally changed the appearance of some products, for example machine tools.

Also, in mechanical engineering many standard components are available for the designer to select rather than design afresh.

The first example concerns the design of a stationary concrete mixer, in which the main function is the conversion of material. It is representative of medium-sized machines produced by batch or mass production. The second example examines the design of a hydraulic control board. It demonstrates how individual sub-systems can be designed in parallel in the course of developing an overall technical system. This second example also illustrates how computers can support the design process. Both examples use special concepts and terms, which have intentionally not been unified. This demonstrates the variety of terms used in design theory and practice, and emphasises that a general approach is possible despite different detailed terms and steps.

Concrete Mixer

Stage 1

This stage, which is often called the *clarification of the task phase*, established the following essential requirements for the stationary concrete mixer: throughput of concrete, mixing quality, mixing time, noise level, external dimensions and production costs. See Fig. 4.1.

Stage 2

Determination of the functions to be fulfilled by the mixer was based initially on the main conversion and on the essential auxiliary conversions which could be deduced from the requirements. Very detailed function structures are to be avoided, because they predetermine solutions and thus make it difficult to optimise the overall solution step by step. On the other hand, a subdivision of the overall function into sub-functions facilitates the utilisation of familiar and well-tried solutions, and assists the rational modularisation of the product (size ranges and modular systems). The main conversion of the mixer is one of materials, mixing sand, gravel, cement and water into concrete. Auxiliary conversions are provided by the drive energy and the control system. The overall function "mix concrete" may be subdivided, for example, into the sub-functions "supply ingredients", "mix ingredients", and "deliver concrete", which are all main functions. Auxiliary functions include, for example, "drive", "support", "seal" and "overload shutdown".

Stage 3

The search for solution principles depends initially on the degree of novelty of the task and on the state of knowledge of the designer. The aim is generally to utilise well-tried and commercially available solutions, particularly for the realisation of auxiliary functions. Individual steps associated with this stage are not applicable for such solutions. In the case of our present example, commercial solutions which are available include electric motors, bearings, gaskets and control elements.

For those sub-functions for which new solutions are necessary, or are important to optimise the product, solutions are found by searching for suitable solution principles, or, if these are not known, by searching for suitable physical effects. They are then realised in principle by establishing their active geometry, active motions and selecting materials (active embodiment features). Such solution principles for the sub-function "mix", for example, are different configurations of mixing blades moving in rotation or translation, and Archimedes screws with various mixing chambers.

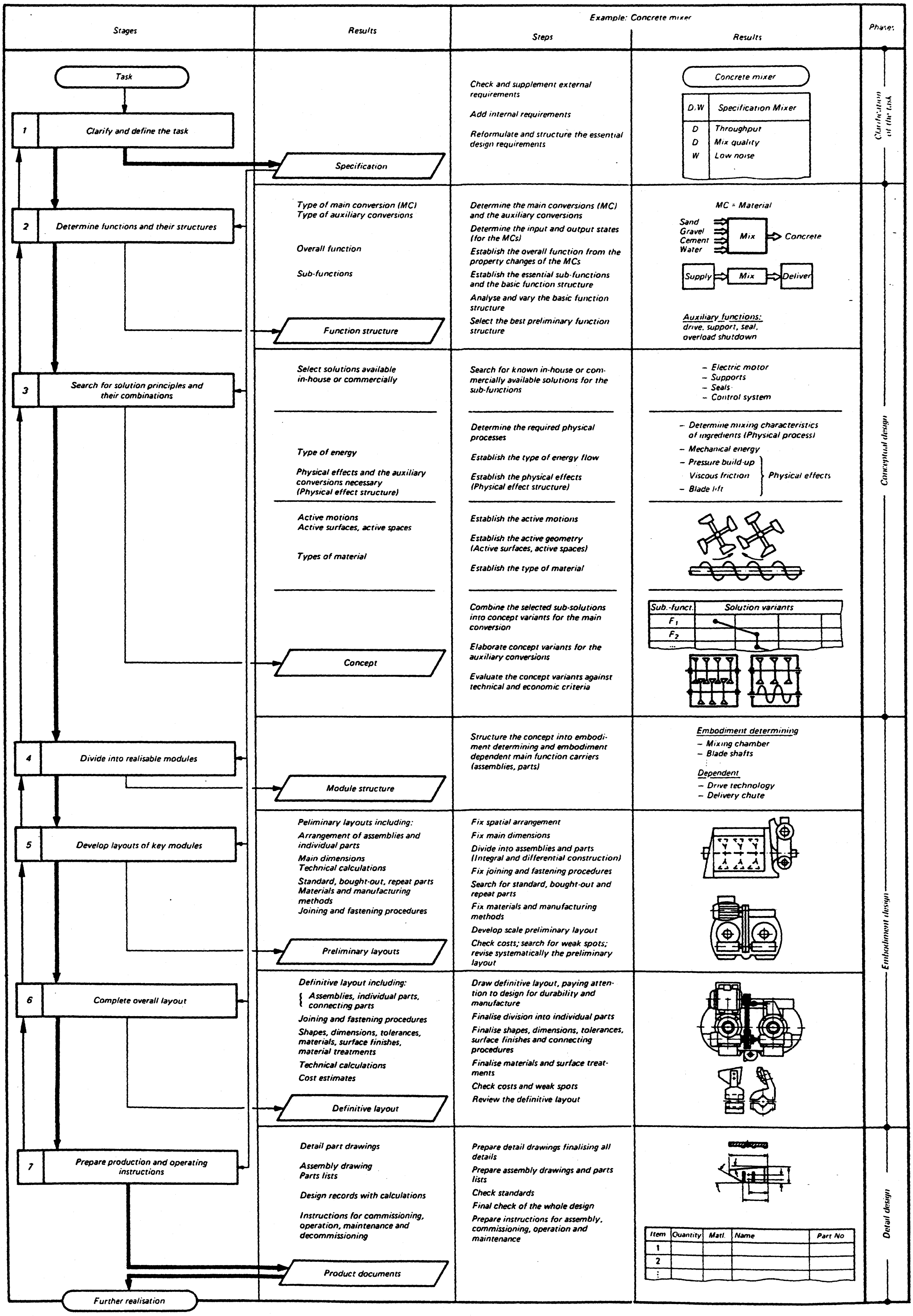


Fig. 4.1. Design process for a stationary concrete mixer

Solution principles which fulfil existing sub-functions must be combined in accordance with the function structure. Such combinations are referred to as concepts. Several concept variants are produced from the wide variety of possible solution principles, from which the most advantageous concept (solution concept) is selected after a technical and economic evaluation. In this case, parallel, counter-rotating, horizontal shafts with projecting mixing blades in an almost square mixing chamber were chosen. Complex experiments with models and prototypes were necessary to determine the definitive concept (see Fig. 3.2).

The detailed steps in this design stage, namely determining the physical effects, establishing the active embodiment features as solution principles and combining the solution principles into a solution concept, can either be executed individually or integrally. This depends on the experience of the designer and on the aids employed, for example design catalogues, or data banks containing physical effects and solution principles (either manual or computerised).

Stages 2 and 3 are often called the *conceptual design phase* in mechanical engineering.

Stage 4

Before the concept is refined further, it is structured into the assemblies and parts which determine the embodiment, that is those which determine the overall layout and main dimensions (main function carriers), The dependent assemblies and parts are then structured. Thus, for example, in the case of the concrete mixer, the mixing chamber and blade shafts determine the overall layout far more than the purchased drive system and delivery chute. This structuring determines the order of the subsequent embodiment design steps and optimisation tasks.

Stage 5

The embodiment design of the key modules proceeds initially only as far as to permit functional optimisation to take place, and important production and assembly techniques to be established. This includes determining: the main dimensions; the arrangement of assemblies and parts, with the key interfaces; and the choice of materials. This stage can include extensive calculations, and leads to preliminary layouts.

Stage 6

To complete the overall layout, the design of the key modules is refined and the embodiment design of all remaining assemblies and parts undertaken. This stage also includes the selection of standard, bought-out and repeat parts. The definitive layout contains all the essential information necessary to prepare the production instructions, which will define individual part shapes, dimensions, tolerances, materials and surface finishes. The production costs can still be influenced in the course of Stages 5 and 6, but the most important influence is exerted by the concept selected in Stage 3.

Stages 4 to 6 are often called the *embodiment design phase* in mechanical engineering.

Stage 7

This stage, which is often called the *detail design phase,* concentrates on the preparation of detail drawings, part and assembly drawings, including parts lists. It also includes detailed production and assembly instructions, test regulations and operating instructions. The result is a complete set of product documents for the manufacture and operation of the product.

Hydraulic Control Board

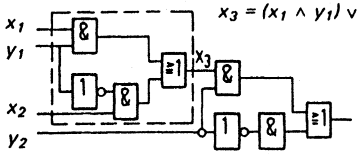
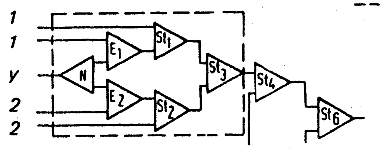
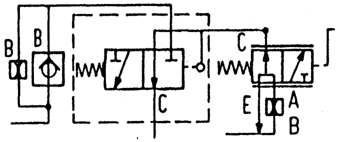
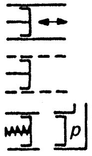
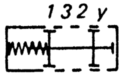
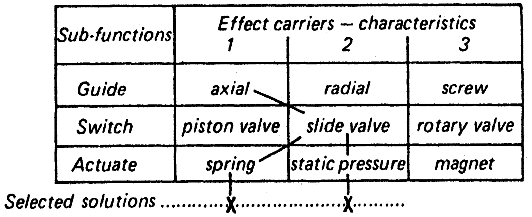
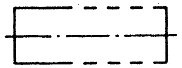
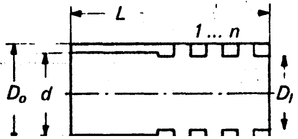
The design of a hydraulic control board, illustrated in Fig. 4. 2, is used as an example of a design task where the greater formalisation of the requirements and of the procedure make it possible to use computers throughout the design process.

"Product-representing models" are used for the formal presentation and computer processing of steps and results. These are defined and manipulated with the aid of "product-defining data" [106]. It will be apparent that the computer-aided approach can be directly related to the general stages proposed in Section 3, which are primarily directed at a manual approach. The slightly different approach described is intended to indicate the variety of concepts used in mechanical engineering and in publications on design methodology. This Guideline goes some way to reduce this variety, but it cannot and should not be completely removed in the interests of a pluralistic development of design methods.

Stage 1

It is important to formulate and structure the requirements, constraints and additional information on the task to be solved. After clarification, they should be elaborated into a specification to facilitate detecting the essential functions and executing the subsequent design stages. In addition to the requirements which are directly relevant to the product, the following are also emphasised:

- the total number of effects and operations necessary to fulfil the *main task* of the product (according to [23]: set of main tasks). This determines the main function and the main conversion of the product in the next stage;

Stages	Results	Example: Hydraulic control board Working aids: Product-representing models (PRM) Manual approach	Computer-aided approach	Computer programs and product-defining data (PDD)	Phases
Task 1 Clarify and define the task	Main task Set of instructions Specification	Task-Representing Models (Languages) Energy flow to control an automatic gearbox for a motor vehicle Design control system using standard components Output power: P = ... (Essential requirement) Maximum length: L ≤ ... (Target requirement) Thermal performance: Constant temp. (Wish)	—	—	Task formulation phase
2 Determine functions and their structures	Logical functions and structures	Function-Representing Models (Symbols) Logic equations, logic diagram	 $x_3 = (x_1 \wedge y_1) \vee (x_2 \wedge \bar{y}_1)$	Drawing system Databank system (logical content and, if applicable, physical effect content) —	Function phase
	Material, energy and information functions Function structures (cybernetics) Function structures	Black-box diagram e. g. general function structure	 -- Directional control valve	Product-defining data (PDD) for the hydraulic circuit diagram: Name of design: .... Number of connections: .... Connection identifiers: .... Valve positions:	
3.1 Search for solution principles Physical effect level	Preliminary selection of main effects	Physical equations (Effects: pressure, pipe flow, Hooke)	$F = A \cdot p; \quad Q = \dfrac{\pi \cdot r^4}{8 \cdot \eta \cdot l} \cdot \Delta p; \quad C = \dfrac{dF}{ds}$		
	Function structure with physical and chemical effects Physical effects, Principle solution	Hydraulic circuit diagram	 -- Directional control valve		
3.2 Search for solution principles Layout level	Active geometry Sketches of effect carriers Layouts, Principle solution	Layout-Representing Models (Drawings) Effect carriers for sub-functions Guide Switch Actuate  Active geometrical unit 	Search Matrix (Morphological Box) 	Databank system — Design catalogues: Guides, Fluid switches, Force generation, Product-defining data (PDD) for the catalogues	
4 Divide into realisable modules		Layout modules Pressure cylinder 	Basic shape of the layout module with variable dimensions Pressure cyclinder 	Drawing system — Computer generated model of the basic shapes with variable geometrical data. Variable numbers	

Search Matrix (Morphological Box)

Sub-functions	Effect carriers – characteristics 1	2	3
Guide	axial	radial	screw
Switch	piston valve	slide valve	rotary valve
Actuate	spring	static pressure	magnet

Selected solutions ............X......................X.........

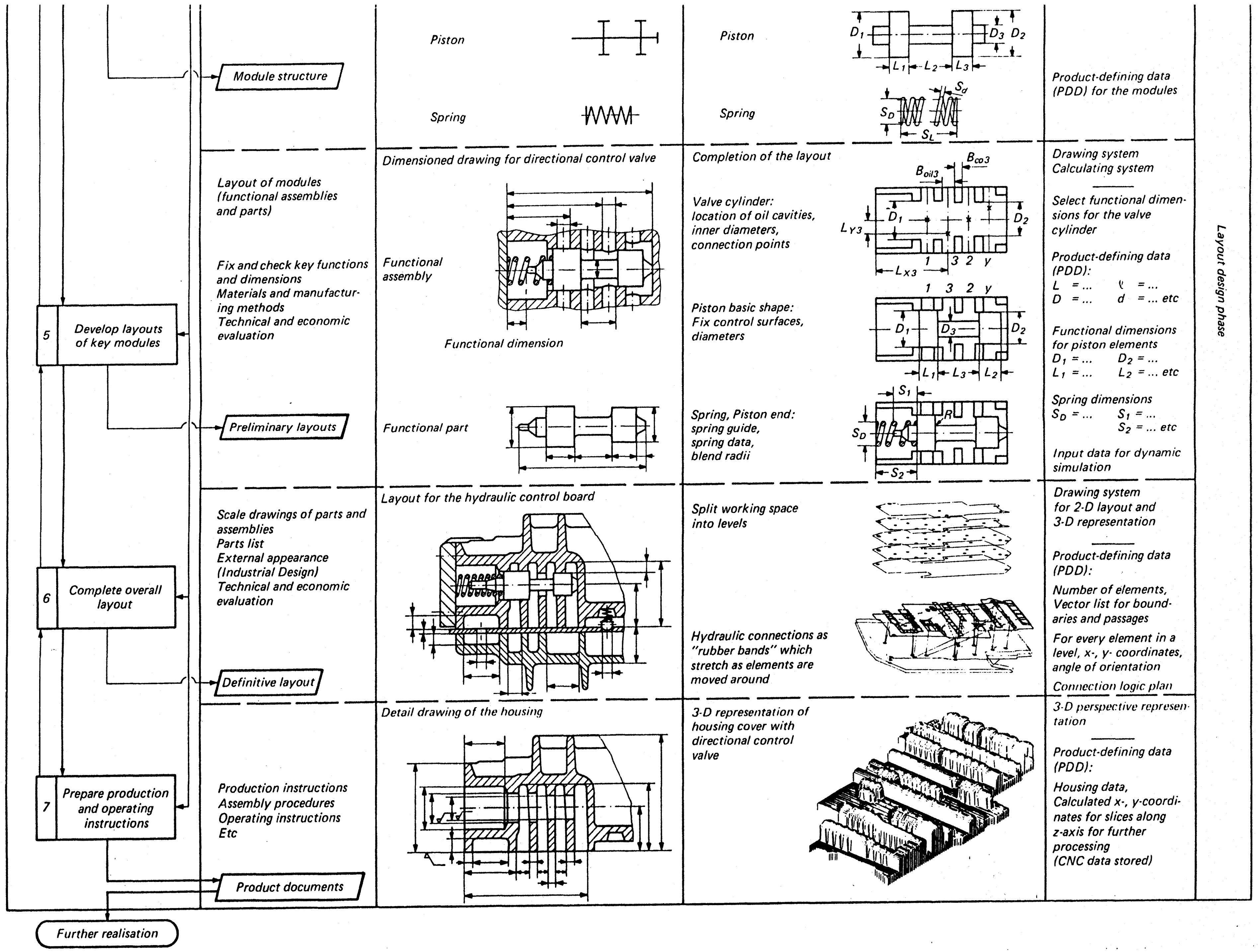


Fig 4.2 Design process for hydraulic control board

- the total *set of instructions* necessary for activities, recommendations and operations required to produce the appropriate product documents (according to [23]: set of instructions).

Task-representing models are used during this stage, usually consisting of language elements formulated in a specific manner. This stage is often called the *task formulation phase*.

Stage 2

The starting point for this stage is to identify the main function to be fulfilled. The main function is the most important component of the overall function, but it can generally be realised only with the aid of auxiliary functions.

It would appear particularly suitable for this example with its overall control function, to produce functions and function structures on a purely logical level (logical function structure) and on the level of material, energy and information conversions (general function structure). Such function structures (function-representing models) can only be processed easily by computers if they consist of a limited number of standard elements, for example technical symbols and their unique combinations. Care should be taken to ensure that in addition to their character content, their logical and physical process content is also contained in the appropriate data structure.

Stage 3

Principle solutions now need to be sought to fulfil the logical and general function structures. In order to achieve a better algorithmic formulation, this stage has been split into two sections.

Stage 3.1

The physical realisation of single functions or of the function structure is done by selecting physical or chemical effects, for example from a design catalogue [23]. These are often described by means of physical equations. For the design of the control board under consideration, the propagation of pressure, laminar flow and Hooke's Law were selected as the main physical effects. The linking of these effects through the function structure leads to a hydraulic circuit diagram, which already represents a principle solution at the purely physical effect level.

A *computer-aided approach* is carried out in the following manner. The hydraulic circuit diagram is stored in the computer with the aid of interpretive programs and product-defining data. These contain the logical operations of the functional units and their connections for use in all subsequent design stages. The hydraulic circuit diagram can easily be constructed and modified on the screen. Aids for Stages 2 and 3.1 include functions, and physical and chemical effects for fulfilling those functions, represented by mathematical, physical and chemical equations or graphic symbols. These two stages are often called the *function phase* [23].

Necessary software: drawing system, program module for the logical combination of elements.

Stage 3.2

Further refinement of the principle solution is undertaken by determining the active geometry, which is formed from the geometrical, kinematic and material features which enable the physical effects to be realised (the effect carriers). Fig. 4.2 examines only the directional control valve with the sub-functions of "guide", "switch" and "actuate". The effect carriers, realised in principle, determine the layout. Their link with the active geometry establishes the *principle solution* by defining the fundamental layout. This fulfils the required functions through physical and chemical processes, and information processing procedures. It is represented in diagrammatic form using layout-representing models.

Naturally, several solutions need to be examined to discover the best. Thus, for example, a rotary rather than a linear principle could have been selected for the valve, but was not for reasons of manufacture and assembly. Working aids during this stage include diagrammatic representations of the components and their connections. They only provide information on the active geometry (active spaces, active surfaces, etc.).

The final layout, derived from the logical and physical contents of the hydraulic circuit diagram, depends essentially on the designer's creativity. At present, a *computer-aided approach* can only assist indirectly, for example if constantly recurring sub-functions and effect carriers are available in a database, possibly in the form of design catalogues. In this case a range of possible solutions can be generated on the screen as a search matrix (morphological box), possibly supplemented with basic graphical representations.

Necessary software: database systems for design catalogues.

Stage 4

When using a manual approach, the division of the principle solution into layout modules to facilitate further processing is not really necessary for such simple assemblies as the directional control valve, but is helpful for more complicated assemblies.

When using a *computer-aided approach*, the design process needs to be divided more finely and, for this reason, modularisation is particularly recommended. It has proved helpful to establish the basic shapes of frequently repeated parts along with special geometrical features such as recesses and openings. The quantities, both in terms of number and size, are completely variable. With the help of the computer, appropriate basic layouts can be drawn with variable dimensions and any required number of special features. Here the specific approach depends on the particular branch of industry considered.

Necessary software: 3-D drawing system for symmetrical and asymmetrical bodies.

Stage 5

The embodiment of the key modules or areas is developed. The preliminary layouts produced show the overall arrangement, main shapes and functional dimensions. They also define essential components, materials, mould seams, assembly procedures and necessary connections. Sufficient information is now available to proceed with detail dimensioning. Aids for this stage are technical drawings of various types.

A *computer-aided approach* can assist with complex calculations, such as volumes and strengths for establishing dimensions, and with combining basic elements into functional assemblies for dynamic simulation. Since all the geometrical data are in the computer, any modifications necessary can be carried out quickly and without error, taking into account the effects on adjacent elements.

Necessary software: as in Stage 4.

Stage 6

When the shapes and sizes of the key functional assemblies have been determined, it is possible to produce the definitive overall layout by completing the embodiment design of the remaining areas, adding any dimensions still missing. This definitive layout should provide sufficient information for a full technical and economic evaluation against the specified requirements. The aids employed are the same as in Stage 5.

When using a *computer-aided approach*, the working space is split into distinct levels. The valves are all placed on one level, say the top level, and the hydraulic connections made in accordance with the hydraulic circuit diagram. The connecting lines initially link the directional control valves to other elements in the form of "stretching rubber bands". This permits the connections to be retained when the valves are moved in order to obtain a non-intersecting layout. A hydraulic layout ready for installation completes this stage of interactive design.

Necessary software: 3-D drawing system and program modules specific to the product, for example for hydraulic layout and for "rubber-band" connections.

Stage 7

The design of the product is concluded by the form design of individual parts. Important information on the production, distribution, application and reuse (recycling) of specific components in the product is documented in the form of production drawings and operating instructions. The aids used are technical drawings, parts lists and instructions.

Using a *computer-aided approach*, it is possible to use the stored geometrical data to generate automatically the shape of the cast housing and then, for example, to produce the data for an NC machine to cut an electrical discharge tool for the manufacture of the mould. During Stages 3.2 to 7 geometrical and technical quantities are manipulated and represented primarily by sketches, drawings and other graphical means, so these stages together are often called the *layout design phase* [23].

4.2 Example from Process Engineering

Introduction

Process engineering is concerned with converting substances chemically, biologically and physically to change their natures, properties and compositions. A chemical process is a complex set of effects, which are linked to each other and to their environment by conversions of material, energy and information. These effects take place in an integrated system of machines and equipment which form the process engineering production plant.

Like all technical systems, a process of converting substances passes through several life phases (Fig. 2.1) [104]. At the outset, the need for a new process is triggered by the requirement for a new substance or for an improvement to an existing process. This need can arise as a result of changes in cost and availability of raw materials and energy, environmental considerations, or technological developments. The technical possibilities are then examined to achieve the desired process in a technically feasible, economically viable and industrially exploitable manner. If the results are favourable at this stage, process design is followed by plant and equipment design with all the necessary detail decisions. This is followed in turn by production and procurement, on site assembly, and commissioning.

Process engineering design has a very considerable influence on the eventual capital requirements and operating costs and it represents a good example of the general approach recommended for each of the life phases of a system. However, it does deviate from the general approach in a number of detailed aspects.

Process engineering design, in common with all design, essentially involves processing information. Gaps in the information frequently become apparent and have to be filled by theoretical and experimental work. These gaps interrupt the cycle of problem-solving, and necessitate independent investigations including: determining substance properties; functional testing of individual pieces of equipment; and, to check overall integration and safety, constructing a pilot plant. Such measures are not apparent from the diagrams in Figs. 3.3 and 4.3. They may be necessary both as phases following the design phase in Fig. 3.2 or as phases running in parallel.

More specialised fields of knowledge tend to be required in process engineering design than in mechanical engineering and precision engineering design. Interdisciplinary cooperation is required between specialists in fields such as: technical chemistry; biotechnology; process engineering; mechanical engineering; production engineering; electrical, instrumentation and control engineering; civil engineering and building construction; safety engineering; and industrial administration. The complexity of such cooperation cannot be reflected in the approach described below. However, the systems engineering approach provides the flexibility for differentiating the overall approach into any required number of detailed stages and steps [101, 102].

Approach

Process engineering design is most suitably divided into three phases of refinement: a preliminary study (feasibility study), a main study and detail studies. The latter may partially overlap the main study in some cases.

The *preliminary study*, which makes extensive use of synthesis and analysis, includes the following steps:

- clarify the need for a new system,
- determine the boundaries of the system,
- define the fundamental requirements,
- examine the fundamental solution principles and their feasibility from technical, economic, political, social, psychological and ecological points of view,
- select the most promising fundamental solution principles with the aid of verifiable evaluation criteria.

The preliminary study also determines the practicability of the chemical or biological reactions, including the selection of raw materials and an examination of the resulting consequences.

The preliminary study thus corresponds to product planning in mechanical engineering as shown in Fig. 3.1. It is often a very large and complex task, and can lead to the project being discontinued if the results are unsatisfactory.

The design phase in Fig. 3.1 is thus equivalent to the *main study plus detail studies*. In the main study, attention is concentrated on the whole process engineering system, developing the results of the preliminary study in order to produce an overall concept on which to base the investment decision. In addition, detail studies are defined in the course of this main study, and priorities set for their execution. Fig. 4.3 shows the levels of the main study which, by analogy, apply also to the preliminary study. In addition, this figure shows how the design process for this particular branch of industry relates to the general design stages described previously.

Stage 1

This stage is usually covered during the preliminary study, particularly if the preliminary and main studies are carried out by the same team. In the event of different departments and personnel being involved, this stage is essential for ensuring that the requirements are precisely expressed in terms of all those involved. Further requirements may be added when the decision to proceed with the project is taken.

Stage 2

Activities during this stage are at the *function level.* The functions to be fulfilled by the process are determined from the *specification*, or from other information available from the preliminary study, and combined into a function structure. The result of this stage is a *basic flow diagram.*

Stage 3

At the *physical effect level,* there follows the search, evaluation and selection of suitable physical effects and operations to fulfil all the functions, such as, for example, evaporation or condensation. The function structure is thus transformed into a process structure and the result of this stage is a *process flow diagram.*

Stage 4

Before searching for suitable plant and equipment to realise the physical operations of the process structure, it is helpful to divide this structure into realisable modules in the form of a *modular process structure.* By doing this, plant and equipment modules which have already proved satisfactory can be identified at an early stage, thus reducing the overall complexity of the task.

Stage 5

At the *embodiment level* the *plant and equipment concepts* must be established or selected for all the key process modules. Where possible these consist of well-tried solutions or of adaptive designs. The level of refinement permissible is determined by the investment decision.

Stage 6

The plant and equipment concepts selected are linked in accordance with the material, energy and signal conversions of the process structure. Additional plant components must be added and, if necessary, detail studies initiated to refine particular aspects of the design. The result is the *pipework and instrumentation flow diagram.*

Stage 7

During this stage, the design is completed and documented to a point at which a definitive *decision on investment* is possible. In order to produce all the documents required for subsequent project planning, production, assembly on site and commissioning it is necessary to carry out many detail studies. The result is referred to as *basic engineering.*

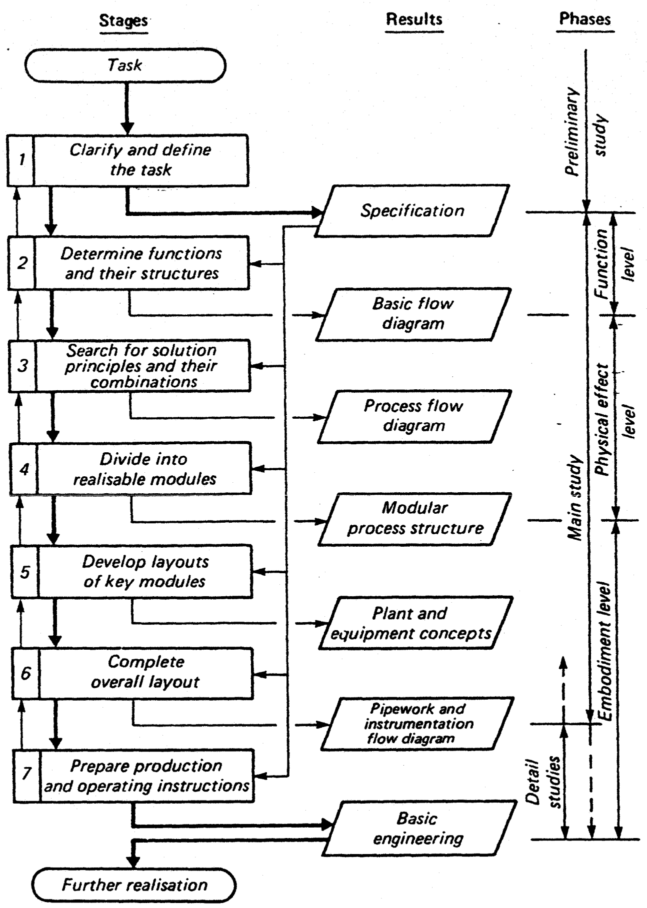


Fig. 4.3. General approach to design in process engineering

The approach adopted subsequently to further realise the design corresponds to that of mechanical engineering.

4.3 Example from Precision Engineering

Introduction

Developments in the field of precision engineering, particularly consumer products, have been decisively influenced by innovations in semiconductor technology and by the wide variety of user requirements. The latter have resulted in external appearance and ergonomics assuming an increasingly important role. The level of integration, which will continue to grow in future, and the miniaturisation of circuits now allow many control tasks previously done by electromechanical means to be solved more economically. Microelectronics also allow new products to be developed with functions and performance features which were simply not possible previously. Integrated circuits, which can be programmed for a specific task, are used extensively. In the design of products in the field of precision engineering, it is therefore necessary for designers from the three specialised fields of electromechanics, electronics and software to cooperate. In the case of products where the decision to purchase depends mainly on their external appearance, it is also necessary for an industrial designer to be involved.

As a rule, precision engineering products are mass produced, requiring high levels of investment in production, sales and service. In conjunction with the frequent need for change, this involves considerable risk. This risk should be minimised by means of thorough development testing before commencing mass production. The need to test models and protoypes in order to optimise the product, make it necessary for the design, manufacture and test cycle to be repeated, see Fig. 3.2. This repetition accounts for a considerable share of the time and costs involved in developing mass produced products.

Approach

In spite of the special circumstances indicated above, the design process follows the general approach presented in Section 3.2, see Fig. 4.4. In this example, each stage will only be described briefly with a few comments, and details will be dispensed with. For the detailed procedure, reference should be made to Guideline VDI 2422, "Methods for Developing Equipment Controlled by Microelectronics".

Stage 1

In this branch of industry, the user requirements seldom come directly from customers, but are determined jointly by several departments within a company. The Design Department is responsible for providing the technical input. The result is a specification (requirements list), and in the case of consumer products possibly a model to indicate the proposed appearance.

Stage 2

The function structure is determined by establishing the information flows between the control system, the overall physical process to be embodied in the product and the user. The function structure is supplemented by an abstract description of the conversion of information at the key interfaces.

Stage 3

Once the means of interactive communication with the user have been determined, the operating and display means can be selected. The overall physical process is split into independent sub-processes, which are coordinated by the control system. Operating and transfer procedures are chosen, active elements selected, sensors determined, and interfaces and connections established. After estimating information flows and the storage requirements, the architecture of the control system can be selected and the control tasks to be carried out by the software determined.

The results of this stage are principle solutions for the three sub-areas. For the *software*, this includes the choice of operating system and a preliminary structure for the application programs. For the *electronics*, this includes: deciding the appropriate circuit technology; selecting the components in the control system; establishing the connections; determining supply voltages; estimating the power and space requirements; producing a concept for the power supply; and providing measures for RF suppression. For the *electromechanics*, this includes: establishing the operating and display layouts, accommodating electrical assemblies; and housing the sub-processes with their conversions of material and energy.

Stage 4

Division within the sub-areas into realisable modules makes it possible to define clearly interfaces between the electromechanics, electronics and software. It is during this stage that the concept is established. The design processes in electromechanics, electronics and software now proceed separately and in parallel, producing results which differ slightly from the general approach, both in terms of their material content and in their nomenclature.

Stages 5 to 7

In the field of *electromechanics*, it is frequently individual transducers (actuators or sensors) which have

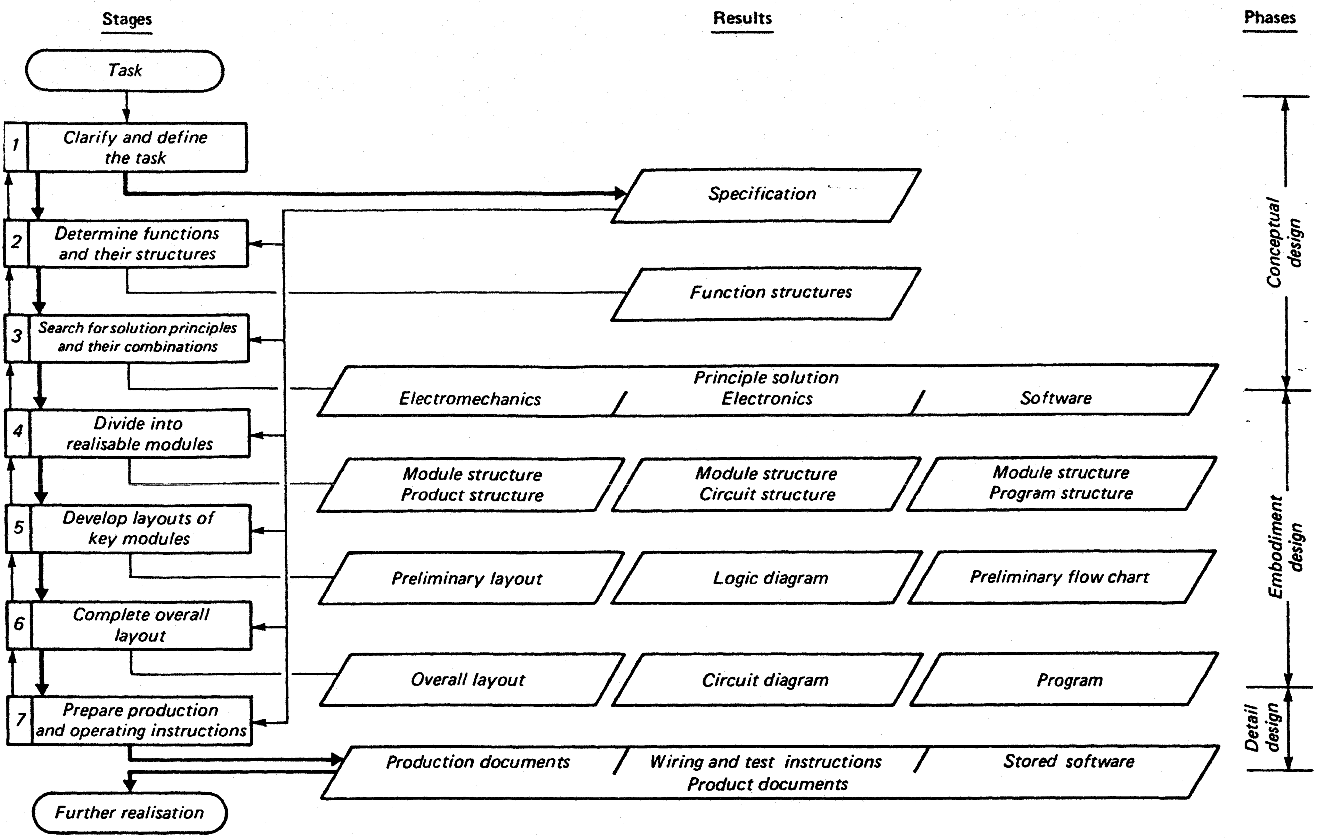


Fig. 4.4. General approach to design in precision engineering

a decisive influence on the overall efficiency and costs. In Stage 5 these transducers are optimised. In Stage 6 the embodiment design of the overall physical process, the display and operating layouts and the electronics, including the control system, is carried out. In Stage 7, detail design, production and operating instructions are prepared.

When optimising the *electronics* many standard modules and components can be utilised, for example control systems, power amplifiers and low-noise amplifiers for the detection of signals. Providing the appropriate power supply is frequently an important factor in the overall cost. In Stages 5 and 6, circuit diagrams and component lists, together with their subdivision into assemblies, are produced. In Stage 7 these are used to develop printed circuit board layouts and the wiring diagrams for assemblies. At the same time, instructions for testing, automatic debugging and adjustment are produced.

Writing the *software* for the control system involves a "top down" approach, that is it starts at the user interface and divides the overall program down until all the detailed control sequences and communication interfaces are defined. Certain critical modules may be examined "bottom up". Structured programming follows in Stage 6. Stage 7 then includes implementation and testing of the program modules using simulation techniques. Finally the program is stored and documented.

Testing

After the results are available from all three subareas, one or several models or prototypes of the product can be manufactured and tested. This stage also includes summarising the results in the form of a complete set of product documents with information on production and operation. The type of model used for testing depends on the stage of the design process reached. During the first stages, function models are used to develop the concept and during Stages 6 and 7, prototypes are used to identify detail design improvements. A full pre-production prototype might be built during Stage 7. Occasionally, even at this late stage, major problems with the design can emerge as a result of testing and necessitate a major redesign.

A special characteristic of precision engineering design resulting from the use of microelectronics is that three distinct design areas must be capable of working independently after the completion of the conceptual phase, see Fig. 3.4. Of course, information is constantly being passed between these areas, but the success of the design process depends largely on how clearly and logically the sub-areas are defined during the conceptual design phase.

4.4 Example from Software Development

Introduction

In addition to mechanical, process and precision engineering, software development can also be regarded as an important area of product design. Software development takes place both as an in-house activity to support other areas of product design, see Section 4.3, and as a specialised activity in software houses, where software is produced either for general application or to specific orders. Software development should be carried out systematically in order to make it possible for it to be planned, optimised and documented. Costs can be reduced by standardising individual program modules, by the application of established procedures and by the careful division of labour.

Approach

The design of software may be viewed analogously to the design of other technical systems [107]. As shown in Fig. 4.5, the design process for software can be related to the stages of the general approach shown in Fig. 3.3. The approach can be split into four main phases:

- *definition phase,* corresponding to Stage 1;
- *design phase,* corresponding to Stages 2 to 4;
- *realisation phase,* corresponding to Stages 5 and 6;
- *documentation phase,* corresponding to Stage 7.

Because of the logical interrelationships, the sequence in which each phase follows another is clearly defined and practically independent of the particular problem. The transfer from the first phase to the next is made by way of a *specification,* which is comparable with the specification or requirements list for mechanical systems. The transfer from the design phase to the realisation phase is by way of a *program flow chart.*

There is little iteration between the main phases. Returning to a phase which has already been completed, resulting, say, in a modification to the program flow chart, is generally not permissible. However, if the resulting program contains fundamental errors, such iterations may be necessary.

Micro-phases occur within the main phases mentioned above and correspond to the stages in the general approach.

The micro-phases are closely related and must be processed systematically following a specific sequence. However, in contrast with the main phases, the sequence is highly iterative, that is the micro-phases within each main phase may be repeated as often as required.

The number and type of micro-phases depend on the particular problem in question. This has a particular effect on the scope and nature of the documentation.

Stage 1

The specification which governs the entire project is determined in this stage.

It is important to gain a deeper understanding of the problem by studying its origin, its environment and the means available for its solution by undertaking a *situation analysis.*

The subsequent *problem definition* consists of formulating a detailed specification which defines exactly the problem to be solved, namely the requirements of the software product. It sets down "what" is to be realised but not "how" it is to be realised. The specification must also contain an exact and complete description of the user's computer system, including the hardware and the system software. Stage 1 is often called the *definition phase.*

Stage 2

In a *function discovery* stage, the overall target functions are broken down into sub-functions based on operational considerations and the interfaces are established roughly. Function discovery can be both procedure-orientated and data-orientated, and hierarchical and functional relationships are possible between the individual sub-functions. The result of this stage is a function structure.

Stage 3

Using the function structure as the starting point, the *principle discovery* stage consists of searching for algorithms and data structures which will realise the sub-functions in principle.

Stage 4

This stage involves *modularisation.* Starting with the function structure and the solution principles, the precise interfaces are established for the program modules and the algorithms formulated in the form of a program flow chart. The result of this stage is a set of requirements for the programmer.

Stages 2 to 4, are often called the *design phase.* They include the development of the functional-logical solution to the problem defined in the specification.

Stage 5

It is the task of *implementation* to convert the functional-logical solution into a program.

The first step in this conversion is characterised by the nature of the flow chart and depends on the

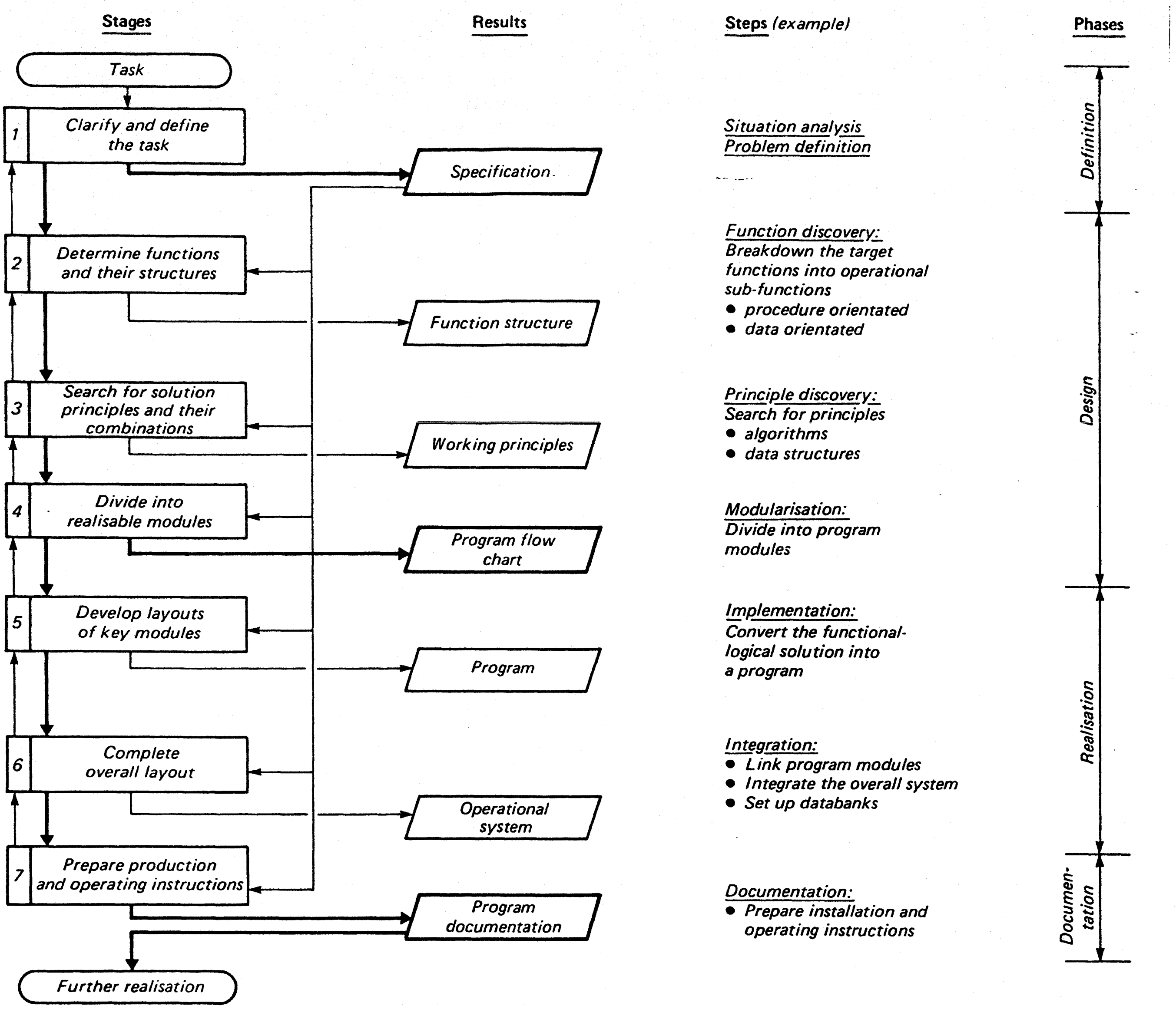


Fig. 4.5. General approach to design in software development

specification and the programming language. Its subsequent steps are translating into source code, editing, testing and debugging.

Stage 6

Integration involves linking individual program modules into an overall system. This includes matching the overall system to its operating environment and setting up databanks.

Stages 5 and 6, are often called the *realisation phase*. They consist of writing the program, in one or several programming languages, to fulfil the specification. The result of this phase is a runnable system, which corresponds to a prototype in mechanical engineering.

Stage 7

Documentation of the results, in the form of manuals for the user and the installer, often takes place independently of the actual software development, though it proceeds in parallel and uses the documents resulting from each of the individual phases.

Further realisation consists of *system installation* at the premises of the user.

5 Methods

In order to undertake and support the various activities and the individual steps in each of the design stages of the general approach, the design engineer requires many methods, procedures and aids. About these much has been written. However, there is often uncertainty in the minds of design engineers about their application in practice, which essentially depends on the following:

- the qualifications, training and experience of the designer;
- the product development programme required to complete the project;
- the size and structure of the company; and
- the potential of the methods themselves.

Since the factors listed above result in many different requirements, it is not possible for the methods developed by a single school of design methodology to fulfil all the requirements on their own in an optimum way. It is necessary that a system of methods should permit the best ones for a particular project to be selected, taking into account the organisational environment and the resources available for the project, such as personnel and finance [44].

The most appropriate selection of methods to undertake the various design stages depends essentially on a more exact knowledge of:

- the overall requirements of the project, the activities required and the available resources; and
- the most important properties and prerequisites of the methods.

The first condition above is usually met since it is fundamental to every systematic approach, including the one described in this Guideline. Sufficient knowledge and experience is not normally available to meet the second condition.

If necessary, projects adopting a more systematic approach can rely on knowledge and skill for the selection of the optimum methods. However, it would be more desirable to have a modular system, from which the most appropriate methods could be selected. Developments with this goal include computer-based method banks and knowledge-based expert systems. However, such systems in a form suitable for application in practice are not yet available.

In order to ease the problems of making a preliminary selection, by providing an overview and by indicating alternatives, established methods are arranged in a matrix, showing their application in the various design stages. The matrix provides a systematic aid for selecting the most appropriate methods for a particular project.

To provide a first orientation, brief notes indicate the principle involved and a rough classification indicates the suitability of the listed methods for the various design stages. Detailed information must be obtained from the references provided. It is in the nature of such a collection of methods and recommended references that it cannot be complete, but only provide a classification scheme for typical methods and some references.

Simply studying the matrix of methods cannot guarantee the successful selection of the best methods and references. Training and practice in selection and application are essential, and so are regular contacts with practitioners and researchers in academic institutions who have knowledge and experience in this area.

Methods / Stages	1	2	3	4	5	6	7
Analysis and goal-setting methods From an analysis of the known or imagined properties of a proposed product and also the characteristics of the product area, goals are derived which provide guiding requirements for the product design process.	**Clarify** and define the task	**Determine** functions and their structures	**Search** for solution principles and their combinations	**Divide** into realisable modules	**Develop** layouts of key modules	**Complete** overall layout	**Prepare** production and operating instructions
Market analysis [1, 2] (Need, price, functions, trends, user groups, target groups, ...)	●					●	●
Prognosis methods [1 to 8] (User groups, need, trends, ...)	●		●				
Competition analysis [1, 2, 9] (Strengths, weaknesses, expected strategies, ...)	●	○	○	○	○	○	●
Competing product analysis [9] (Performance, costs, strengths, weaknesses, functions, technology, ...)	●	●	●	●	●	●	○
Company analysis [10 to 12] (Finances, personnel, production facilities, ...)	●		○	○	○		
Product planning [1 to 14, 70, 71] (Innovation, marketing, user groups, target groups, ...)	●	○				○	●
Problem analysis [1 to 11] (ABC-analysis, analysis of potential problems, ...)	●	○	○	●	●	●	○
Definition of goals [9, 11, 12, 15, 17 to 20] (Functions, price, costs, market, target groups, ...)	●	○	○	○	●	●	●
Analysis and specification of product properties Important prerequisites for a successful search for the solution to a technically and economically optimised new product are: the abstraction of the required properties in the form of functions; the division and structuring of those functions; and the clarification of the conditions, quantified where possible, imposed on possible solutions.							
Describing functions through:							
– Verbal definitions (noun and verb) [15, 16, 18, 19, 21 to 24, 90]	○	●	●	●			
– Elementary physical effect functions and basic operations [15 to 25]		●	●	○			
– Mathematical representation in the form of algorithms, equations, computer models, ... [17, 20, 23, 25, 26, 29, 64, 74, 78, 91 to 94]		○	○	○	●	○	○
– Drawings, models, technical sketches [27], 3-D models [28], perspective drawings such as those common in Industrial Design [75 to 77]	○	○	○	●	●	●	●
Structuring functions through:							
– Hierarchy of functions (function tree) [15, 16, 18, 19, 24]		●	●	●			
– Linked function structure (function net) [17 to 20, 23 to 25]		○	○	○			
– Verbal function track (FAST/logical function path) [15, 21, 22]		●	●	●			
– Mathematical models [17, 20, 23 to 26, 29]					○		
Quantification of requirements through:							
– Specification (requirements list) [15, 17 to 20, 23 to 25, 108]	●	●	●	●	●	○	○
– Technical weighting (rating the quality of the proposed solution against an "ideal" one fulfilling all the functions) [19, 29]	○					○	○
Simulation and similarity analysis [64, 67, 72, 73]		○	●		●	●	
Structural mechanics (Finite Element Methods) [78]					●	●	

● well suited ○ suitable
for the respective stage

Stages Methods	1	2	3	4	5	6	7
Methods for developing solution ideas A minimum prerequisite for the development of an optimum solution is to have available as many solution ideas as possible. After the abstract representation of functions has opened up the largest possible search field, a combination of heuristic and discursive techniques should lead to many good quality ideas. Working through the various steps iteratively is a characteristic of searching for solution ideas.	**Clarify** and define the task	**Determine** functions and their structures	**Search** for solution principles and their combinations	**Divide** into realisable modules	**Develop** layouts of key modules	**Complete** overall layout	**Prepare** production and operating instructions
Intuitive methods (heuristics) for solving poorly structured [31, 103] and non-algorithmic problems, and for stimulating human creativity							
Creativity techniques [31 to 33, 37]							
– Brainstorming [34] for triggering associations of ideas within a team	○	●	●				
– Method 66 [32] for including almost any number of participants		●	●	○			
– Method 635 [32] for searching with a team when time is short		●	●	○			
– Provocation [31] for triggering associations using pictures, key words, questions, ...			○		○		
– Delphi [31] for collecting ideas through written questioning of 15 to 20 anonymous participants, for example when highly-qualified specialists are unable to meet together [82]	○		○	○			
Systematic-discursive methods [30 to 33, 36, 37] for solving well structured [31] and algorithmic problems							
Morphology [36]							
– Morphological boxes [23, 35, 36, 90] in the form of a 2- (3-, ...) dimensional matrix for the systematic collection, arrangement and combination of solution elements		●	●	●	○		
– Reduced morphology [30, 36] using a combination matrix in which incompatible combinations are suppressed in order to reduce the overall number of combinations		●	●	●	○		
– Property lists [36] as 2-dimensional morphological boxes for combining solution elements		○	●	●			
Systematic variation, for example of physical effects [17 to 20, 23 to 25], of structure, of layout, ... [89]		○	●	○	●	●	
Design/solution catalogues [23, 38, 109, 110] as a comprehensive collection of possible solutions or solution elements for developing solution variants		●	●	○	●	●	
Design rules and guidelines: embodiment design procedure [18], basic rules [18], embodiment design guidelines [18], for example designing for: production [18, 39]; assembly [113]; ergonomics [18, 40]; recycling [18, 41]; minimum noise [42]; integration of functions [95, 96]				●	●	●	●
Modular systems and size ranges [18, 43, 44] for optimising the technical and economic properties, the overall scheduling and the application of products, processes, organisational resources, systematic methods, procedures, etc., through the realisation of similar sub-functions using modules or size range elements		●	○	●	●	●	●
Combinations (heuristic/discursive)							
Combinations of the above methods or method elements: systematic modular system [44]		○	○	○	○	○	○
Synectics [45]: creating new thought models by using unfamiliar analogies, often non-technical, and using these to analyse and develop the problem	○	●	●				
– Reduced synectics: reducing the scope of the analogies, for example associating bio-mechanics problems with biological analogies [46 to 48]		○	●	○	○	○	

● well suited ○ suitable
for the respective stage

Methods / Stages	1	2	3	4	5	6	7
Cost calculation and economic assessment procedures The optimisation of a product requires consideration of the overall technical and economic situation, and procedures for analysing and predicting production costs must proceed alongside the assessment of the technical properties of the product.	**Clarify** and define the task	**Determine** functions and their structures	**Search** for solution principles and their combinations	**Divide** into realisable modules	**Develop** layouts of key modules	**Complete** overall layout	**Prepare** production and operating instructions
Calculation procedures [49 to 53] for determining the absolute costs for the total product development (design and production)							
Cost comparison calculations [83]: a comparison between solution variants where only *differences* in cost allocation are considered	○		○		●	●	●
Complete cost calculation [49 to 53]: all the company costs are fully allocated to the products				○	●	●	●
Break-even analysis: the appropriate proportion of the fixed costs of the company are added to the variable costs of a particular product and compared with the revenue earned by that product [49 to 53]	○		○		●	●	●
Overhead calculation: fixed costs are covered by the allocation of a percentage overhead based on specific product costs, for example wages, variable costs, material costs, ... [49 to 53]				○	●	●	●
Marginal cost calculation [49 to 53]: assessment of the variable costs of a product, without attempting to cover the fixed costs, in order to determine a lower price limit	○			○	●	●	●
Early cost estimation methods for determining the absolute and relative costs of a product as early as possible during its development [29, 49 to 59]	○	○	●	●	●	●	○
Relative cost catalogues [29, 58]: based on cost factors such as component shape, material and manufacturing complexity, all identified by a code number, the overall cost of different designs can be compared. The method does not permit absolute costs to be determined and relies on the cost relations existing at the time the catalogue was produced.				○	●	●	○
Short calculation [60]: determining absolute costs by considering a number of parameters to describe products, including complex ones			○	○	●	●	○
Cost growth calculation [61]: consideration of physical similarities			○	○	●	○	○
– Similarity calculation [51, 55]: consideration of general similarities (in addition to physical ones) of components, manufacturing processes, calculation principles, company structures, etc.			○	○	●	○	○
Economic assessment in the form of cost-benefit analysis where the product is considered as a complete system [67], starting with its initial creation, continuing through its operation and ending with its scrapping [53]	●		○		●	●	●
Investment calculation [9, 66] for determining the required investment for the total product development and its subsequent amortisation	●				○	○	●
Estimation theory [29] with common algorithms for determining design principles and component dimensions from both a technical *and* an economic point of view			○	○	●	○	○

● well suited ○ suitable
for the respective stage

Stages Methods	1	2	3	4	5	6	7
Evaluation procedures and decision techniques Through evaluation and selection against technical, economic and general criteria (target functions, cost goals, safety), the overall number of solution ideas is reduced. After further evaluation the most suitable one is selected. After working through the design steps in an iterative manner, a decision about the optimum overall solution is made [9, 15, 16, 61 to 66]	**Clarify** and define the task	**Determine** functions and their structures	**Search** for solution principles and their combinations	**Divide** into realisable modules	**Develop** layouts of key modules	**Complete** overall layout	**Prepare** production and operating instructions
3-stage selection (suitable – possibly suitable – not suitable) for a first approximate categorisation of the solution ideas, particularly when using heuristic methods to find ideas [82]	o	o	●	●	●	●	
3-criteria evaluation (advantages – disadvantages – costs) for a comparative evaluation of solution ideas and suggestions [82]	o	o	●	●	●	●	●
Dual comparison [9]: using an evaluation criterion, each pair of ideas, from a large number, is systematically compared	o	o	●	●	●	●	o
Cost-benefit analysis [9, 63] for determining the economic value of a product, or component, during all or part of its lifetime	●	o	o	o	●	●	●
Use-value analysis [9, 63] for determining the value rating of a solution suggestion for each of several evaluation criteria. The sum of the values for each criterion is the overall value of the solution suggestion. The optimal solution is the one with the highest overall value.	o	o	●	●	●	●	●
Technical and economic evaluation [29]: by plotting the technical rating and the economic rating of a product as the abscissa and ordinate of a graph respectively, it is possible to make an assessment depending on its position relative to the diagonal. A balanced product lies on the diagonal, an expensive one below the diagonal and a technically weak one above the diagonal.		o	●	●	●	●	●
Weak spot analysis and disturbing factor analysis [18, 20, 58, 112] for recognising and minimising unfavourable product properties		o	●		●	●	
Fault-tree analysis: analysis of potential sources of system failure using AND/OR relationships for possible system element faults [97]		●	o		o	●	●
Expert appraisal, if necessary using a checklist, provides a fast systematic-intuitive evaluation procedure which is useful in many situations, particularly with poorly structured [31] problems. The results should be checked using other evaluation procedures.	o	o		o	o	o	o
Operations research [64] for optimising well structured and algorithmic problems using mathematical methods	o		o	o	o	o	o
Decision criteria matrix [65, 16]: decision criteria are weighted and the various solution variants are evaluated using a value scale based on points or on costs			●	●	●	●	
Relevance or decision tree [66]: the relationships between decisions are represented in the form of a tree so that the ranking and importance of each decision can be seen			●	●	o	o	

● well suited o suitable
for the respective stage

Stages Methods	1	2	3	4	5	6	7
Integrated methods (action models) The systematic procedures described in this Guideline are based on or extended by other methods used to help with the solution of technical and related problems. Above all, the computer offers a new range of possibilities for systematic design.	**Clarify** and define the task	**Determine** functions and their structures	**Search** for solution principles and their combinations	**Divide** into realisable modules	**Develop** layouts of key modules	**Complete** overall layout	**Prepare** production and operating instructions
Systems engineering [67, 101]: a basic method for the description of systems of any type and for the solution of problems which arise in those systems. All problem-solving methods can be considered as applied systems engineering.	●	●	●	●	○	○	○
Value analysis [15, 16, 66]: a problem-solving procedure which is widely used in industry. In its practical application it takes into account the combined effects and mutual influences of three components: methods, procedures and management. A retrospective fourth component is the result produced by the above three.	●	●	●	●	●	●	●
Design methodology [17 to 20, 23 to 25, 29, 68]: a procedure developed in German universities which has extended the application of systems engineering to the design of technical products	●	●	●	●	●	●	●
Computer-aided design and manufacture							
CAE, CAD/CAM, CIM, ... [69, 91, 93, 94, 103]: the same internal computer model used to describe the shape, dimensions, materials, etc. of components can be used to produce working drawings and parts lists and also to prepare production plans, NC-programs, stock lists, requisition orders, cost breakdowns, etc.					○	○	●
Computer graphics for static and dynamic modelling			○	○	●	●	●
6-stage methods (work study) [82]	○	○	○	○	○	○	○
Team working [87] has advantages compared to individual working because of the additional knowledge available, the synergy effects and the group dynamics. The solutions produced by a team tend to have greater authority and acceptability.	●	●	●	●	●	●	●
Management methods							
Management by ... (management behaviour) [84]	●	○	○	○	○	●	●
Project management [85, 86]	○	○		○	○	○	○
Planning methods [70, 71]	●	○		○	○	○	●
Network planning [79 to 81, 88] for planning the schedule and estimating the earliest and latest end date for a course of events, including essential events which lie on the critical path	○			○	○	○	●
Capacity planning [3, 9, 80, 88] for the allocation of existing capacity and for the procurement of additional capacity for design, development, manufacture and assembly	○				○	○	●
Investment planning for the procurement or construction of manufacturing plant, computer facilities, test equipment, buildings, etc. [9, 12, 88]	○				○	○	○
Optimisation calculations [64, 72, 73] for multi-parameter linear or non-linear optimisation procedures to extend the standard engineering science calculations [74]					○	○	○
Industrial Design [75 to 77, 98 to 100] for handling and optimising the man-machine interface [40]	●		●	●	●	●	●

● well suited ○ suitable
for the respective stage

6 Terminology

The following definitions of terms have been limited to those which are important for understanding this Guideline, and to those which would appear to make a contribution to a generally applicable systematic approach to design. It has not been possible to standardise the terms completely, as some are specific to one branch of industry and some to a particular school of design methodology. This should cause few problems if they are taken in context. For more detailed definitions, the reader should consult the references.

A direct translation of some terms from German into English is difficult. The aim has been to convey the sense of the German original in clear manner rather than to achieve a rigorous word for word translation. Because of this, minor inconsistencies are bound to arise, but it is hoped that they are few and far between and that they do not detract from the main flow of the argument.

Translating the various terms used for "design" and the "design phases" is not straightforward and a few points of explanation might be helpful. The *design process* is part of the total *product development* activity. This Guideline describes a *general approach* for the *systematic design* of *technical systems* and *products*, which are made up of *assemblies, sub-assemblies, components* and *parts*. The general approach is divided into an appropriate number of *design phases*, and these, in turn, are divided into *design stages* and, where necessary, these are further subdivided into *design steps*.

The design process in *mechanical engineering*, for example, is generally split into four phases: *clarification of the task; conceptual design; embodiment design;* and *detail design*. Most of these terms are familiar, but embodiment design may need some clarification. Other publications have used *layout design, main design, general arrangement design, scheme design* and *draft design* for this phase, which involves the development of a more or less abstract concept into a more concrete proposal, usually represented by a *layout drawing*. Embodiment design overlaps detail design and incorporates, as appropriate, both *layout design* (the layout, arrangement or disposition of assemblies, components and parts and their relative motions) and *form design* (the shapes, dimensions and materials of individual parts). In many translations, form design is used in a wider sense, that is the form design of the whole product.

Possibly other unfamiliar terms are those derived from words such as "Wirkfläche" and "Wirkbewegung". There is no accepted direct translation, and for the German prefix "Wirk-" the English word "active", in the sense opposite to "passive", is used. The above two German terms are therefore translated as "active surface" and "active motion", that is the surface or the motion responsible for the effect *of particular interest* at the time.

Active Area (Active Geometry, Active Motion, Active Space, Active Surface, Etc)

The area (geometry, motion, space, surface, etc) of an assembly or part which is contributing to the → effect *of particular interest* at the time.

Active Principle (Working Principle)

Fundamental law or principle governing the → effect *of particular interest* at the time.

Algorithm

Fixed, clear, finite series of steps and rules, which when followed lead to a precise solution of one class of problem.

Auxiliary Function

Any → function which is not a → main function. A particular → sub-function can be an auxiliary function for a → product and also a → main function for a sub-assembly of that product.

Conceptual Design

Development and representation of a → function structure and the search for → solution principles and their structures in accordance with the → task and the → specification. The result is a → principle solution or a concept.

Design Process

Totality of the activities with which all the information necessary for producing and operating a → technical system or → product is processed in accordance with the → task. The result is a set of → product documents.

Design Phase

A set of related design activities or → design stages in the → design process. For example the task clarification phase, the conceptual design phase, the embodiment design phase and the detail design phase.

Design Stage

A limited set of design activities within a → design phase of → systematic design.

Design Step

An individual activity within a → design stage of → systematic design.

Detail Design

Elaboration of clear definitions for all the details for the production and operation of a → product in accordance with the → specification. The result is a set of → product documents.

Effect

A repeatable, predictable occurrence of a physical, chemical, biological or data processing nature.

Effect Carrier

A particular physical element (shape, surface or arrangement) or combination of elements, or instructions in the case of computer programs, producing an → effect.

Embodiment Design

Elaboration of the arrangement and shapes of the elements in a → product, and, where appropriate, the preliminary selection of materials, in accordance with the → principle solution and the → specification. The result is a → layout design (preliminary or definitive).

Form Design

Totality of all detailed activities through which the elements of a → product are determined, that is the geometrical shapes of parts, their dimensions, surface finishes, materials, and their overall combination into a product. In the case of nonmaterial products, for example software systems, form design is the activity of defining in detail the elements of a program, and their combination into an overall solution. The result is a set of detail drawings or detailed descriptions.

Function

Relationship between input, output and state variables of a system independent of a particular solution. A distinction is made between → overall function and → sub-function, and between → main function and → auxiliary function.

The concept of "function" is also used in the natural and engineering sciences to represent a physical or mathematical relationship, for example in the form of an equation.

Function Structure

Arrangement of individual → functions. Relationship between the → overall function and the → sub-functions.

Industrial Design

That part of the design process which concentrates on the external appearance and ergonomics of a product, that is the man-machine interface.

Layout Design

The activities involved in laying out or arranging the elements (assemblies, components, parts) of a → product. The result is a layout drawing.

Main Function

The → function describing an essential requirement of a → product.

Model (Product-Representing Model)

Abstract or concrete representations of a → product or part of a product, for example functional model, simulation, computer model, mock-up, etc. They are used to demonstrate the functions, properties or features of solutions in whole or in part. Embodiment details and inessential → requirements can be omitted.

Overall Function

Totality of all → functions which a → product realises or is intended to realise. The overall function is derived from the → task and can be broken down into → sub-functions.

Principle

Fundamental law governing a basic → effect.

Principle Solution

Combination of → solution principles for all the functions in a function structure.

Product

Hardware or software produced as the result the → design process.

Product Development

Purposeful application of the results of research and experience, for example of a technical or economic nature. The total sequence of activities required to create a new → product, including design, development, manufacture, assembly, installation and operation. The results can include new products and computer programs.

Product Documents

All the documents required for producing and operating the product.

Prototype

First physical realisation of a → product.

Requirements

Qualitative and quantitative definition of the functions and constraints to be fulfilled by a → product. Different weightings can be given to the requirements.

Result

Result of a → design phase, → design stage or → design step.

Solution Principle

Fundamental solution of one or more linked → functions by selecting → effects and essential embodiment features.

Specification (Requirements List)

Collection of → requirements for a → product formulated in writing. The specification forms the basis of the → task at the start of the → design process and should be kept up-to-date during the course of this process.

Structure

Representation of parts of a whole and their relationship to each other.

Sub-Function

Every → function produced by the subdivision o a superior function. Subfunctions can be → mai functions or → auxiliary functions. Sub-function can be arranged into a hierarchy.

Systematic Design

The systematic, stepwise planning and executio of the → design process, and the theory supporting this approach.

Task

Set of instructions to create a new → product. I contains the essential starting information for th process of design, and indicates the essential an desirable → functions and properties. In addition it contains information on schedules, costs an organisational procedures.

Technical System

Set of ordered and connected technical element related to their environment by inputs and outputs at the system boundary, for example → product.

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Modelling the Design Process in Engineering and in Architecture

NIGEL CROSS & NORBERT ROOZENBURG

SUMMARY *Models of the design process in engineering seem to have converged upon a consensus represented, for example, by the German VDI model. However, after starting from common origins, models of the design process in architecture have diverged from the engineering consensus, in response to criticisms from both theorists and practitioners. There now appear to be significant differences between the engineering and architectural design models. Criticisms of the consensus model of engineering design have also been made, similar in some ways to the earlier criticisms of the architectural design models. We discuss the similarities and differences between the two consensus models—in engineering and architecture—and identify prescriptive* vs. *descriptive emphases. We suggest that attempts should be made to reintegrate the two models to improve common features of design education and practice across the disciplines.*

1. Introduction

This paper is concerned with the differences that have arisen between models of the design process in different disciplines, especially between engineering and architecture. We find these differences both interesting and informative, especially since early models of the design process in these disciplines had common origins and substantial similarities. We propose in this paper to analyse the differences that have emerged and to suggest the need to reintegrate the models.

2. Consensus Model of the Engineering Design Process

In engineering design, models of the design process have been developed since the early 1960s. This development has converged to what might be called a consensus model. The model is described in some VDI publications [1, 2] and in slightly different versions in several textbooks (see, in particular, Pahl and Beitz [3] and Hubka [4]). German engineering designers have been the main contributors to the development of the consensus model. Comparable models, though less detailed and less precise, are those of Van den Kroonenberg [5] in The Netherlands, and French [6] and Pugh [7] in the UK.

The consensus model portrays the engineering design process as a sequence of activities, leading to certain intermediate results: performance specification, function

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structure, principal solution, modular structure (concept), preliminary layout, definitive layout, documentation (see Fig. 1). The activities are usually grouped into four phases: clarification of the task, conceptual design, embodiment design and detail design.

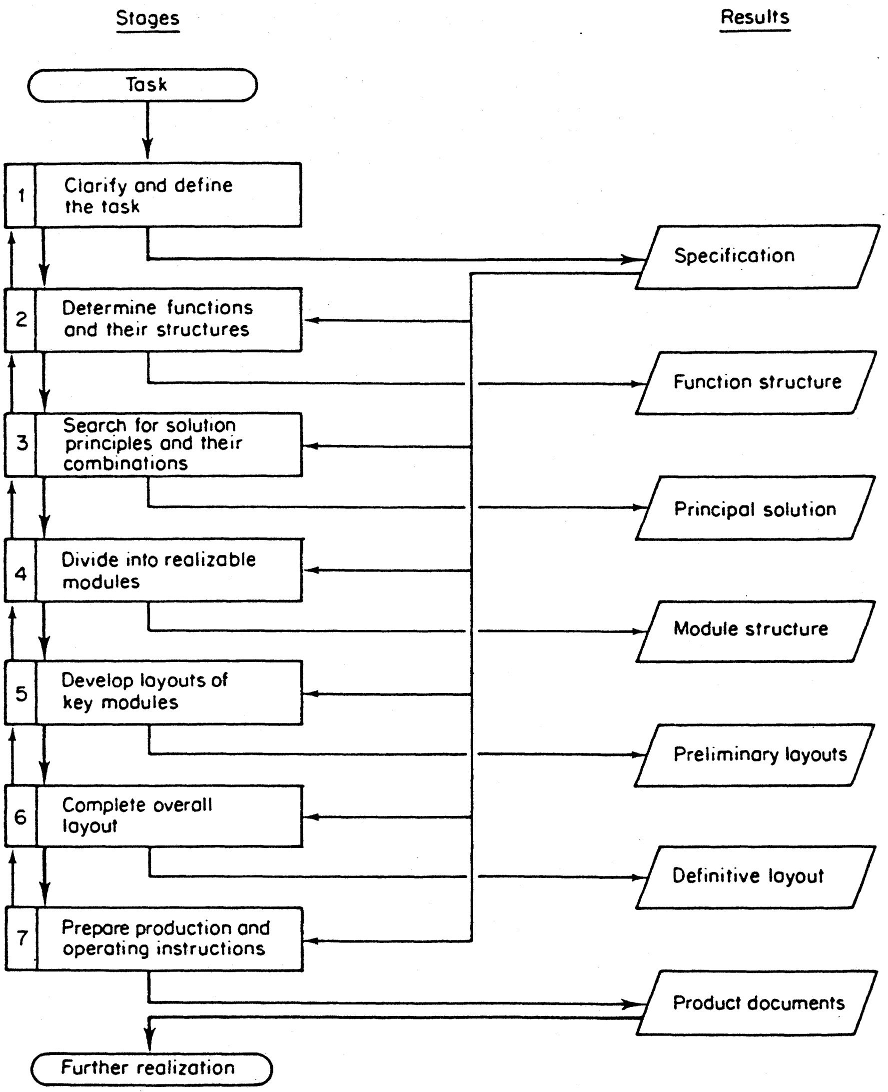

FIG. 1. VDI model of the engineering design process.

This consensus model is fundamentally derived from the ways in which engineering design problems are conventionally perceived and modelled. Machines and products are technical systems that transform energy, material and information. The functional behaviour of a technical system is fully determined by physical principles and can be described by physical laws. The engineering design problem is to find and define the geometry and the materials of the system in such a way that the required prespecified physical behaviour is realized in the most effective and efficient way. Amongst others, Hubka and Eder [8] have set out these fundamentals in great detail.

Underlying this model is a structure based upon a systems engineering approach to the development of complex systems. According to this approach, development projects are to be structured in two 'dimensions'. The vertical dimension corresponds to the origination phases in the life cycle of a product (such as feasibility study, preliminary design, detailed design, planning for production, planning for distribution, planning for retirement). The horizontal dimension is the problem-solving process that takes place in every phase of the vertical structure: analysing and defining problems, synthesizing solutions, simulating or predicting performance, and evaluating and choosing the best system. This two-dimensional view can be traced to Hall [9] (see Fig. 2); Asimow [10] was one of the first who applied this view to modelling the engineering design process.

STEPS OF THE FINE STRUCTURE (Logic) -----> PHASES OF THE COARSE STRUCTURE (Time)	1 Problem Definition	2 Value System Design (develop objectives & criteria)	3 Systems Synthesis (collect & invent alternatives)	4 Systems Analysis (deduce consequences of alternatives)	5 Optimization of Alternatives (iteration of Steps 1 - 4)	6 Decision Making (application of value system)	7 Planning for Action (to implement next phase)
1 Program Planning							
2 Project Planning (and preliminary design)							
3 System Development (implement project plan)							
4 Production (or construction)							
5 Distribution (and phase in)							
6 Operations (or consumption)							
7 Retirement (and phase out)							

FIG. 2. Hall's morphology of the systems engineering process.

However, the consensus model of engineering design tends to emphasize the vertical dimension of this underlying structure. The horizontal dimension is not strongly represented and possibly that is why this dimension is sometimes overlooked —not so much by its authors (see, for instance, Pahl [11] and Hubka [4]) but by its users and, above all, its critics, leading to faulty arguments and misinterpretations of the model.

Two further characteristics of the consensus model should be mentioned. Firstly, it assumes that design should proceed from the general and abstract to the particular and concrete, i.e. the problem should be analysed in abstract terms, before any material concepts are established, and those concepts are then gradually refined in increasingly more detail. Secondly, it assumes that complex problems should be decomposed into subproblems, for which subsolutions are to be found and 'synthesized' into overall solutions for the design problem (see Fig. 3).

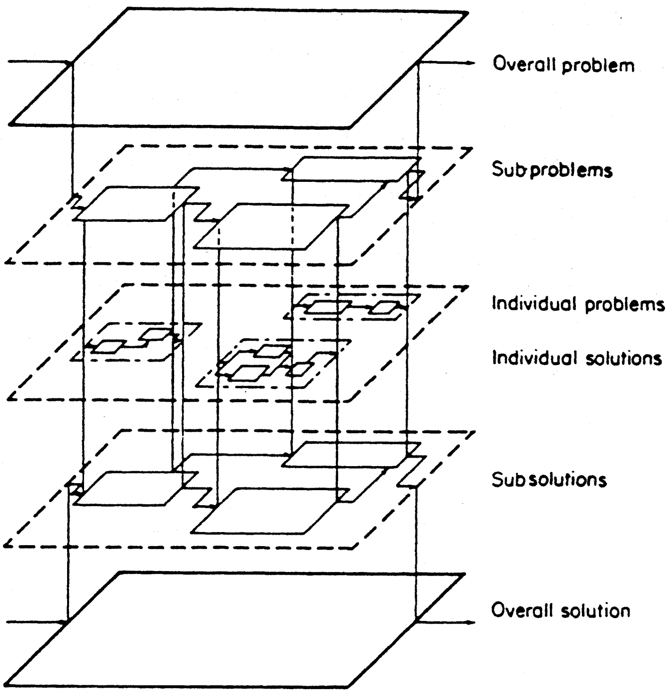

FIG. 3. VDI view of problem decomposition and solution synthesis.

By specifying in its vertical structure a set of intermediate results to aim for, without prescribing in detail how these intermediate results are to be obtained, the consensus model does not restrict designers to just one way of working. Instead, it tries to organize the problem-solving behaviour of designers so that this behaviour will be more effective and efficient than intuitive, unaided, unsystematic ways of working. The consensus model is a 'methodology', though it is a weak or heuristic one. It is a weak methodology because it is built upon weak knowledge (experience) about the consequences of the possible actions to be taken (in terms of the insights gained with respect to design decisions). It is a heuristic methodology because following it requires 'sensible' (knowledgeable or informed) interpretation by the designer of the vaguely defined 'rules' and terms and—even if properly applied—success is not guaranteed.

3. Developments in Architectural Design Methodology

Early models of the design process in architecture were often very similar to models of the engineering design process. For example, the model of architectural design developed by Marcus and Maver [12] (see Fig. 4) had similarities to the model of engineering design by Asimow. The editors of the 1962 *Proceedings of the Conference on Design Methods* [13], Jones and Thornley, represented engineering design and architectural design, respectively, and both used similar models to help describe and teach the design process. In industrial design there was also a similar basic model of the design process represented by Archer [14] (see Fig. 5).

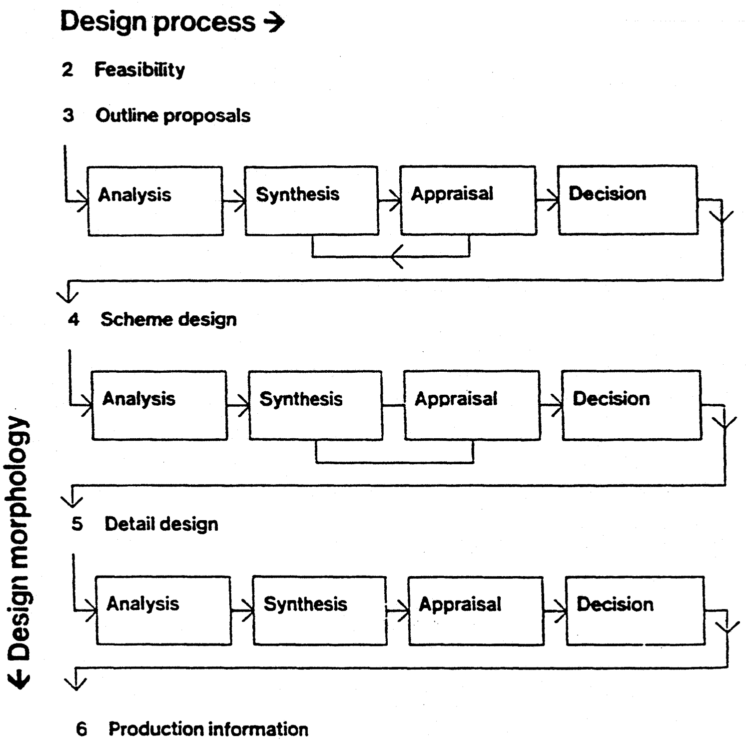

FIG. 4. Maver's model of the architectural design process.

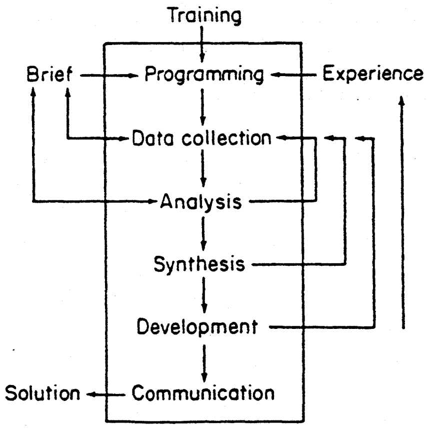

FIG. 5. Archer's model of the industrial design process.

However, in the early 1970s, architectural design methodologists began to criticize this shared view of the design process. Hillier *et al.* [15] were among the first to question the orthodox view that designers should resist bringing their own preconceptions to bear on the problem. They argued that designers not only do but inevitably must 'prestructure' their problems in order to solve them. They suggested that the prevailing 'analysis–synthesis' model of design (in which exhaustive problem analysis must precede solution synthesis) was derived from a fallacious view of the role of inductive logic in science and that designers have to rely on a form of preconception —their prior knowledge of solution types. Hillier *et al.* therefore proposed a model of design based (like Popper's view of science) on the centrality of conjectures. In this 'conjecture–analysis' model, the designer must first generate a solution conjecture which is then subjected to analysis and evaluation, rather than analysis preceding synthesis or conjecture. (Similar arguments and proposals in a systems engineering context have also been made by Rzevski [16].)

Later, Darke [17] developed this model a little further. Based on interviews with architects, she proposed a 'generator–conjecture–analysis' model, which prominently identified the role of a 'primary generator' in design. According to Darke, very early in the design process the designer imposes (or identifies) a particular, strong generating concept or a particular, limited set of design objectives. This again contradicts the view that the design process must begin with an exhaustive problem specification, from which solution concepts may then be synthesized. Instead, solution concepts are seen to be based on 'primary generators' or 'prestructures'.

March [18] also argued that the essential logic of the design process requires that solution concepts are produced not by analytical, inductive or deductive reasoning but by 'productive' reasoning (a form of Peirce's 'abduction'). (A comparable argument with respect to the logic of design was developed by Eekels [19] and by Roozenburg [20].) March outlined a rational design process as consisting of "(1) the creation of a novel composition, which is accomplished by productive reasoning; (2) the prediction of performance characteristics, which is accomplished by deduction; and (3) the accumulation of habitual notions and established values, an evolving typology, which is accomplished by induction". He proposed a 'P–D–I' model of the design process: an iterative procedure of production–deduction–induction (see Fig. 6). The production of a design proposal, March suggested, must be based on an initial statement of requirements and on a presupposition or protomodel. There is similarity here to Hillier *et al.*; they suggested a model comprising prestructures–conjecture–analysis and March suggests one comprising presuppositions–conjecture–analysis–evaluation.

The nature of design problems also came under scrutiny. Rittel and Webber [21] argued that design problems in architecture and planning are inherently ill-defined (or, as they called them, 'wicked') problems. They pointed to the limitations of the analytical approach to wicked problems, and characterized design as a multidisciplinary 'argumentative' process. It is now widely recognized that design problems are ill-defined problems.

The result of these criticisms and reformulations of the design process in architecture appears to have been a general rejection of any linear, sequential, analysis–synthesis–evaluation scheme. There is no well-formulated consensus model of the design process in architecture (nor any longer in industrial design) but we may conclude that there has emerged a 'type model' with the following features:

- it has essentially a spiral structure;
- it recognizes the importance of prestructures, presuppositions or protomodels as the origins of solution concepts;
- it emphasizes a conjecture–analysis cycle in which the designer and the other

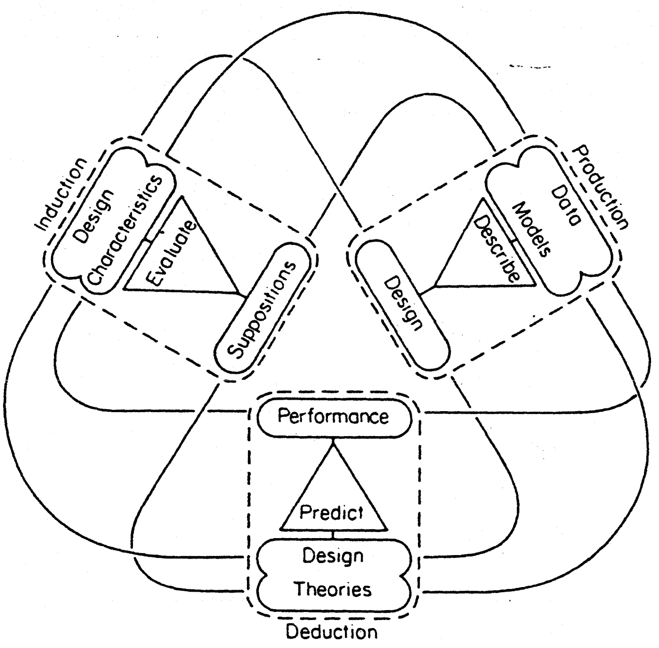

FIG. 6. March's model of the architectural design process.

participants refine their understanding of both the solution and the problem in parallel;

- it assumes design problems, by definition, to be ill-defined problems.

These and other related arguments and developments have been presented by Cross [22].

In retrospect, we might say that in architecture and industrial design the attention of the design researchers and theorists shifted from the vertical (linear, procedural) dimension of the design process to the horizontal (iterative, problem-solving) dimension.

4. Differences between the Models

After starting from common origins, there now appear to be significant differences between the consensus or type models of the process of engineering design and that of the process of architectural design. A major difference is the apparently linear, sequential nature of the engineering model *vs* the spiral, cyclical nature of the architecture model. Models of the engineering design process tend to emphasize the sequence of stages through which a project is expected to progress (e.g. concept–embodiment–detail stages), whereas the models of architecture and industrial design emphasize the cycle of cognitive processes that the designer is required to perform (e.g. productive–deductive–inductive thinking). In emphasizing the sequence of stages that is expected to occur during project development, the engineering model is more *prescriptive*; in emphasizing the thought-processes that have to be employed by the designer, the architecture models are more *descriptive*.

In both architecture and engineering, it was at first proposed that solution concepts should be synthesized only after rigorous and exhaustive analysis of user requirements and other basic features of the problem. Architectural design methodologists now stress the importance of generating solution concepts early in the design process, drawing upon presuppositions. This shift is also a reflection of the prescriptive–descriptive split.

Another example of divergence from a once shared view is concerned with representations of problem structure. The engineering design consensus model is based on a view of the problem structure as essentially a tree-like structure; the overall problem can be broken down into distinct subproblems, each with sub-subproblems, etc. After initially assuming that architectural and planning problems could also be hierarchically decomposed as trees, Alexander [23] soon specifically rejected this view [24], and most planners, architects and industrial designers now accept this.

There may be some straightforward reasons for these differences between the models. In particular, the knowledge domains of the professions are different. Architects lack, for their essential problems, the equivalent of the engineering sciences that are available for engineering designers; the architects therefore have to rely much more on trial-and-error design procedures. Architects also tend to view their design problems as inherently ill-defined problems, whereas engineers' problems are more usually well defined.

There may also be fundamental differences related to preferences in cognitive styles between engineers and architects. Such a dichotomy might arise because of differences between engineering's science-based, problem-focused education and architecture's arts-based, solution-focused education, as suggested by Lawson [25]. Cross [26] identified cognitive styles (such as serialist *vs* holist, convergent *vs* divergent) with 'designing styles' and suggested that models of the design process by different authors also could be characterized as representing different cognitive styles. Thus, some models represent a serialistic design strategy, while others are holistic, some represent a convergent design strategy, while others a divergent design strategy.

The characteristics of the consensus models of engineering design and architectural design are contrasted in Table I.

TABLE I. Comparison of characteristics of the engineering and architecture models

Characteristics of the engineering model	Characteristics of the architecture model
Assumes problems are (or can be) well defined	Assumes problems are ill-defined
Systematic, expert process	Opportunistic, argumentative process
Starts with problem-analysis; avoids preconceptions	Starts with solution-conjecture; accepts prestructures
Linear	Cyclical
Tree-like problem structure	Lattice problem structure
Prescriptive of design behaviour	Descriptive of design behaviour

5. Criticisms of the Consensus Model of Engineering design

The consensus model of engineering design has not been without criticism. To begin with, it has been observed that the model has been developed with the design of new, innovative technical systems in mind. Therefore it pays too much attention to the conceptual design phase at the expense of the phases of embodiment and detailed design [11, 27]. In practice, many product design projects can or must do without the 'invention' of new technical principles and start from known, 'proven' concepts. However, the consensus model offers little procedural advice with respect to embodiment and detailed design. It has even been questioned whether detailed procedural models for these phases may exist [28, 29], because the decisions to be taken in these phases are strongly interrelated, owing to the complexity of technical systems. The process in these phases is essentially one of continuously refining a concept, jumping from one subproblem to another, anticipating decisions still to be taken and correcting earlier decisions in the light of the current state of the design proposal. Therefore, it seems that the iterative problem-solving model mirrors these phases better than does a linear procedural model.

As in architecture, the model of engineering design has also been criticized from an empirical point of view. In practice, the behaviour of engineering designers very seldom resembles the behaviour prescribed by the consensus model. Several authors [27, 30, 31] have stated that, contrary to what the consensus model assumes, working from abstract problem formulations to concrete solutions and splitting problems into subproblems are iterative and recursive processes that rely upon anticipations of possible solutions. As such these observations do not disqualify the model, because it is a prescriptive model that intends to structure, and not to predict, design behaviour, but there is not much sense in prescribing 'impossible' behaviour. However, there is until now little empirical evidence in favour of the effectiveness of the model contrasted to conventional intuitive ways of working, or against it. Empirical research into the engineering design process is only beginning to gain momentum, so opinions on the value of the model as a heuristic method for engineering design are still largely based on personal experiences and beliefs in its rationality.

The model has also been criticized from a methodological point of view. For instance, function structures might be of limited heuristic value [32], partitioning the design process into a large number of small steps might lead to an uncontrollable explosion of possible solutions [30] and often, when appearance is important, the total form of a product has to be determined before or in relation to the form of the parts (as 'dictated' by the chosen principles [2, 33]).

6. Towards Reintegration of the Models

We believe that there are good reasons for trying to get the consensus or type models to converge, i.e. for seeking to integrate the two types into a common version again. It is clear that both models have particular strengths and weaknesses. For example, it is obvious that all designers need to progress their projects in a sequence of stages, similar to the engineering model; it is also obvious that designers must employ varying cognitive procedures during the design process, as in the architectural model. In contrast, a weakness of the engineering model is that it emphasizes problem analysis and specification, perhaps at the expense of innovative solution generation; a weakness of the architecture model is that it emphasizes early solution conjectures, perhaps at the expense of adequate problem clarification. A more developed, generalized model of the design process would integrate the strengths of both models, while avoiding their weaknesses.

In particular, it is in design education that integrated models are now urgently required. If a design education curriculum is based on extreme versions of either type model, then not only do we risk training future designers with impoverished understanding of the nature of design and with crippled design ability, but also we shall lose the benefits and progress that genuinely have been made in the course of developing both the consensus models over the recent decades. These comments apply not only to the education of professional designers but also—and perhaps especially—to the rapidly growing development of design in general education (i.e. in the schools), where the educational weaknesses of simplified models of the design process have already been criticized [34].

An integrated model is still a long way off although some authors have attempted to move towards it [35]. The present authors have also each attempted some integration in their recent books. Roozenburg and Eekels [36] deal with both type models. They consider the basic design cycle (see. Fig. 7), a model of the problem-solving process in design, as the more fundamental model, and use this cycle (instead of a linear procedural model) as the frame of reference for the discussion of methodological problems and methods.

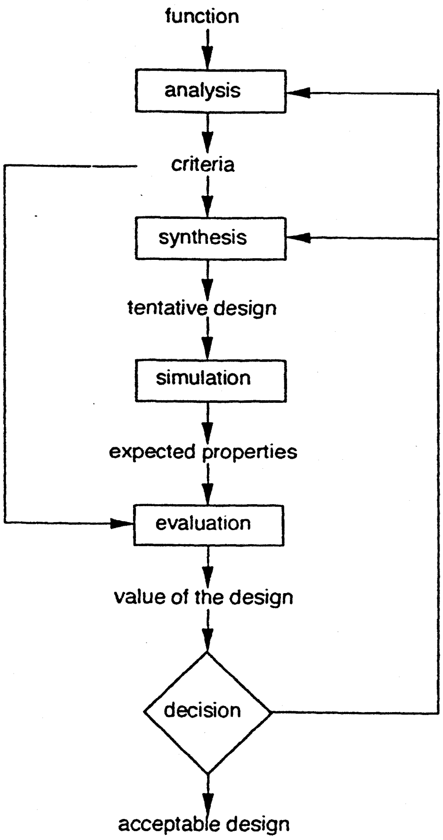

FIG. 7. Roozenburg and Eekel's model of the basic design cycle.

Cross [37] has proposed a 'hybrid model'—it has descriptive and prescriptive traits—(see Fig. 8) with the following features. Firstly, a symmetrical relationship is assumed between problem and solution, and between subproblems and subsolutions. This attempts to demonstrate and indicate that the relationship is not one way from problem to solution, but that problem definition is often dependent upon solution concepts. This is an acknowledgement that making solution conjectures is often a means of helping to clarify the problem. At lower levels, there are similar interactions between identifying subproblems and generating subsolutions. The upper and lower double-headed arrows in Fig. 8 indicate that the designer's thinking will oscillate to-and-fro between problem/subproblems and solution/subsolutions.

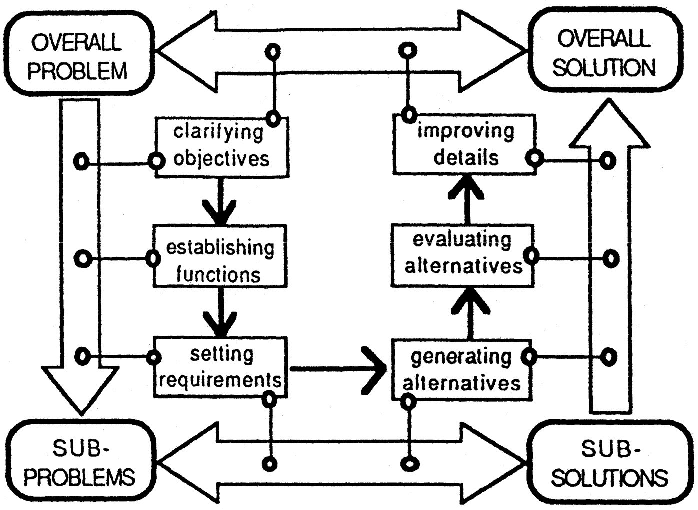

FIG. 8. Cross's model of the engineering product design process.

Secondly, there is a hierarchical relationship between problem and subproblems, and between solution and subsolutions. This attempts to demonstrate and indicate that an important and inescapable part of problem clarification is the activity of decomposing it into subproblems, for example, by identifying subfunctions and specifying performance requirements. On the other side of Fig. 8 is indicated the necessity of building the overall solution from subsolutions, for example, by generating, combining, evaluating and choosing appropriate subsolutions. The descending and ascending arrows at the left and right of the diagram indicate that the designer will expect to progress from problem to subproblems and from subsolutions to solution.

Finally, within this overall framework there is a proposed set of design activities (which are related to a set of design methods). These activities and methods promote and assist the design process, whether this is exploring the problem–solution relationship, decomposing problems into subproblems or synthesizing subsolutions. It should be noted that the activities could also be presented as a sequential process, starting with 'clarifying objectives' and ending with 'improving details'.

7. Conclusion

We have discussed some positive and negative features of both consensus models. The consensus model of engineering design is essentially a concise prescription of the tasks in a design process. It is strong in its rationality—as founded in the theory of technical systems—but has some shortcomings with respect to the cognitive processes that take place in the heads of designers. In contrast, the models that nowadays prevail in architecture reflect design as it is carried out by practitioners. These models are primarily descriptive and, hence, they offer little guidance to those who believe—as we do—that better ways of working than those in practice are possible and worthwhile to develop.

We have argued for the need to make a reintegration of the consensus models of engineering and architecture, building on the strengths of each. Good models will be built upon rationality adapted to the properties and features of the tasks to be performed, and to the cognitive characteristics of the designer. This calls for an integration of the insights that have been gained from design methodology in both engineering and architecture, if design practice in general is to benefit from these insights. Above all, it is in education that models of the design process are needed that are neither overly prescriptive nor weakly permissive, but are reliable, robust and formative of good design behaviour.

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3 Descriptieve theorieën over ontwerpen

- Rittel, H. and M.W. Webber, Planning Problems are Wicked Problems. In: Cross, N. (ed), *Developments in Design Methodology*, Wiley, 1984.

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In het vorige deel van deze reader werden prescriptieve modellen van het ontwerpproces besproken. Daarin wordt beschreven hoe een ontwerpproces doorlopen zou moeten worden. Deze modellen zijn hoofdzakelijk ontstaan uit twee bronnen: praktijkervaringen van ontwerpers, en het theoretiseren van ontwerpers en ontwerpmethodologen over hoe het beter zou kunnen. In dit deel van de reader staan een aantal artikelen waarin - soms stevige - kritiek op deze modellen wordt geuit. Meestal komt die kritiek voort uit onderzoek naar het werkelijke verloop van ontwerpprocessen in de praktijk. Vandaar dat dit deel de titel 'descriptieve theorieën van het ontwerpen' heeft meegekregen.

Het eerste artikel *Planning Problems are Wicked Problems* van Rittel en Webber sluit aan bij Hoofdstuk 4 'Wat is ontwerpen?' van het boek *Produktontwerpen*. In dat hoofdstuk wordt de kern van het ontwerpen gedefinieerd als het bedenken van de vorm en de gebruikswijze van een product, gegeven uitspraken over het beoogde gedrag van het nieuwe product in de vorm van uitspraken over functies en/of gewenste eigenschappen. Dit 'terug redeneren' van Functie naar Vorm blijkt geen deductief proces te kunnen zijn, en kan daarom niet buiten intuïtie en creativiteit. Elke (aankomend) ontwerper weet dat natuurlijk uit eigen ervaring, maar in het boek wordt met behulp van wat formele logica tot op zekere hoogte bewezen dat dit zo is!
In het boek 'Produktontwerpen' blijven echter veel vragen onbeantwoord. Bijvoorbeeld: wat zijn de kenmerken van ontwerpproblemen, waarin verschillen ontwerpproblemen van andere problemen (zoals het oplossen van een wiskundig vraagstuk), welke verschillende soorten van ontwerpproblemen zijn te onderscheiden (en in hoeverre vragen die om een andere aanpak), en wat maakt ontwerpproblemen nu juist zo 'problematisch' om op te lossen (als dat al zo is)?
Aan dit soort vragen hebben ontwerpmethodologen veel aandacht geschonken, vanuit de

gedachte dat een helder inzicht in de aard en structuur van ontwerpproblemen één van de voorwaarden is om betere ontwerpmethoden te bedenken.

Als belangrijkste kenmerk van ontwerpproblemen wordt in de literatuur vaak het feit genoemd dat ontwerpproblemen zich voordoen als 'slecht-gedefinieerde' ('ill-defined', 'ill-structured', 'wicked') problemen. Deze gedachte werd voor het eerst in de zestiger jaren onder meer door Horst Rittel naar voren gebracht. Rittel was een wiskundige en ontwerper, die aan de Hochschule für Gestaltung (HfG) in Ulm les heeft gegeven, en, naast Christopher Alexander, Bruce Archer en Christopher Jones, één van de ontwerpmethodologen van het eerste uur. Rittel zocht een alternatief voor de lineaire, stap-voor-stap modellen van het ontwerpproces die in die tijd gangbaar waren. Er waren veel varianten, maar die schreven allemaal een stringente scheiding voor tussen het definiëren en het oplossen van problemen.

Probleem-definiëren werd gezien als een 'analytisch' proces waarin ontwerpers zo onbevooroordeeld mogelijk de 'onderdelen' of 'aspecten' van het probleem bepaalden en de eisen t.a.v. de oplossingen formuleerden. Probleem-oplossen werd gezien als een 'synthese' van deeloplossingen voor de verschillende aspecten en eisen. (Voor voorbeelden van dit soort modellen, zie Archer's *Basic design procedure* in het inleidende artikel, Lawson's *Descriptions of the design process* en Cross & Roozenburg's *Modelling the design process*). In praktijk bleek echter dat ontwerpprocessen niet in een lineair keurslijf te dwingen zijn en dus zo ook meestal niet verlopen. Rittel meende dat dit komt omdat ontwerpproblemen 'wicked problems' zijn. Hij had daarbij overigens de meer grootschalige ontwerpprocessen op het gebied van stedebouw, openbaar vervoer, onderwijsontwikkeling, e.d. op het oog. Voor Rittel zijn 'wicked problems': 'a class of social system problems which are ill-formulated, where information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing.' Deze karakterisering lijkt ook heel goed op architectuur en productontwerpen van toepassing. In het artikel in de reader sommen Rittel en Webber 10 eigenschappen van 'wicked problems' op. Bijvoorbeeld: er is geen 'definitive' (niet één enig juiste) formulering van dit soort problemen mogelijk; welke informatie relevant is hangt af van het soort van oplossingen waaraan men denkt. Het formuleren van het probleem *is* het probleem. 'One cannot understand the problem without knowing about its context; one cannot meaningfully search for information without the orientation of a solution concept; one cannot first understand, then solve'. Dergelijke gedachten brachten Rittel en Webber (en vele andere ontwerpmethodologen) tot het afwijzen van de vroege, op de 'systems approach' gebaseerde methoden van ontwerpen, die berustten op eerst uitvoerig informatie verzamelen, dan analyse van de gegevens, en pas daarna - als een afzonderlijke fase -het genereren van oplossingen. Zij zagen ontwerpen veel meer als een iteratief proces waarin het beeld van het probleem zich in wisselwerking met het beeld van de oplossing ontwikkelt, onder invloed van de uitwisseling van opvattingen en ideeën van de betrokkenen bij het proces.

Het idee dat ontwerpproblemen slecht-gedefinieerde problemen zijn en dat de zogenaamde 'first-generation' methoden te star waren en gebaseerd op een verkeerd beeld van ontwerpproblemen heeft algemeen ingang gevonden. Maar er is ook kritiek op geuit. Zo heeft bijvoorbeeld H. Simon betoogd dat er geen scherpe grens is tussen 'ill-structured' en 'well-structured' problemen; er is eerder sprake van een spectrum dat loopt van slecht tot goed gestructureerd. Zo bezien kan ook eigenlijk niet gezegd worden dat elk ontwerpprobleem slecht-gedefinieerd is, want ook bij het ontwerpen komt men problemen uit het hele spectrum tegen. En is het niet juist een kenmerk van ontwerpprocessen dat aanvankelijk slecht-gedefinieerd problemen in het ontwerpproces overgaan (of behoren te gaan) in goed-gedefinieerde problemen door de interpretaties en beslissingen van ontwerpers?

Herbert Simon is een eminent denker (Nobelprijswinnaar!) die heel veel invloed heeft gehad op hoe wij ontwerpen zien. In het *artikel Problem Forming, Problem Finding, and Problem Solving in Design* geeft hij een kort overzicht van zijn theorieën.

Die vinden hun oorsprong in het onderzoek dat er vanaf de jaren zestig onder andere door de pioniers op het gebied van de Kunstmatige Intelligentie is gedaan naar 'problem Solving': om computers te maken die zelfstandig problemen zouden kunnen oplossen werd er onderzocht hoe mensen dat nu eigenlijk doen. Daartoe werden veel proeven gedaan (onder andere door Herbert Simon) waarin proefpersonen geobserveerd werden terwijl ze bezig waren met het oplossen van eenvoudige schaakproblemen, geometrische puzzeltjes en wiskundige vergelijkingen. Deze proeven leverden veel inzicht over de basisfactoren die een rol spelen bij probleemoplossen, en de verschillende probleemoplos-strategiën die mensen er op na houden. Herbert Simon was een van de eersten die ook wees op de beperkingen van dit onderzoek: hoe kun je op basis van theorieën die je ontwikkelt aan de hand van zulke simpele puzzeltjes uitspraken doen over zeer ingewikkelde processen als ontwerpen?
In dit artikel beschrijft Simon het ontwerpen als een zeer speciale vorm van probleemoplossen waarbij hij sterk de nadruk legt op het verschil tussen ontwerpen en het oplossen van zulke eenvoudige puzzeltjes. Daarbij doet hij als scherp observator en bijzonder helder analyticus een aantal uitspraken die je als ontwerper direct zult herkennen.
Op een aantal punten verklaart hij ook het gedrag van ontwerpers door te wijzen op de cognitieve beperkingen die mensen nu eenmaal hebben. Zo kunnen we maar aan een beprkt aantal dingen tegelijk in ons korte termijn geheugen (onze 'aandacht') houden, en gebruiken we tekst en tekeningen als een soort 'extern korte termijn geheugen' om deze beperking te omzeilen.

Bryan Lawson is een architectuur docent die grote bekendheid heeft verworven met zijn empirische en theoretische studies van het ontwerpproces. Uit zijn boek *How Designers Think*, hebben we twee delen overgenomen. In *Descriptions of the design process* kritiseert Lawson de prescriptieve modellen (die hij 'maps' noemt) vanuit empirische bevindingen over het feitelijke gedrag van ontwerpers. Zijn eerste punt van kritiek is dat deze modellen eigenlijk geen echte 'maps' voor een ontwerper zijn: het zijn 'descriptions not of the process but of the products of that process. They tell us not how architects work but rather what they produce in terms of feasibility reports, sketch plans, production drawings, and what they do in terms of obtaining planning approval and supervising the construction of the building.' Met andere woorden, het zijn meer hulpmiddelen voor het management van ontwerp-processen dan voor het ontwerpen als zodanig. Zijn andere punt van kritiek is dat de gangbare prescriptieve modellen onvoldoende inspelen op het specifieke karakter van ontwerpproblemen ('ill-defined problems') en op de 'solution-focused' werkwijze van ontwerpers in de praktijk; met dat laatste bedoelt hij dat veel ontwerpers al vroeg in het proces oplossingen overwegen als hulpmiddel om het probleem te doorgronden.
In *Problems and Solutions* geeft Lawson een kernachtige samenvatting van de belangrijkste karakteristieken van ontwerpproblemen en -oplossingen enerzijds, en het ontwerpproces anderzijds.

In het vierde artikel *A dialogue concerning at least two design worlds* van Bucciarelli en Schön weerklinken een aantal ontwikkelingen die deze eeuw in de wetenschapsfilosofie hebben plaatsgevonden. Tot ca 1950 werd het bedrijven van wetenschap nog overwegend als een rationele activiteit gezien. In die opvatting wordt wetenschap gekenmerkt door een specifieke methode of familie van methoden en zijn het in laatste instantie alleen neutrale feiten en logica die over het wel en wee van wetenschappelijke beweringen beslissen. Onder meer Kuhn's paradigmatheorie en Feyerabend's aanval op het idee van een universele wetenschappelijk methode hebben geleid tot de relativering van dit logisch-positivistische ideaalbeeld van wetenschap. Feiten zijn in meer of mindere mate theoriegeladen of zelfs sociale constructies en naast argumenten (logica) zijn ook sociale factoren en maatschappelijke belangen van (doorslaggevende) invloed op de inhoud van wetenschappelijke kennis. Kennis kan op heel verschillende wijzen worden verkregen en wetenschappelijke kennis kan geen aanspraak maken

op een bijzondere status *uitsluitend* omdat via 'wetenschappelijke' methoden te werk zou worden gegaan.
Een recente en zeer relativistische interpretatie van wetenschap is het sociaal-constructivisme. Uitgangspunt daarvan is dat feiten niet klaar liggen om ontdekt te worden maar dat zij het resultaat zijn van sociale processen waarin over de waarheid van beweringen *onderhandeld* wordt op basis van belangen van betrokken partijen. Feiten worden in deze opvatting sociaal geconstrueerd. Tegenover het traditionele idee dat wetenschappers concensus (moeten) bereiken door een beroep op feiten en methodologische regels stellen sociaal-constructivisten dat wetenschappelijke feiten juist het gevolg zijn van consensus die in sociale processen tot stand komt (Kroes, P., Ideaalbeelden van wetenschap, Boom, 1996).
Dergelijke ontwikkelingen in de wetenschapsfilosofie hebben ook de ontwerpmethodologie niet onberoerd gelaten en geinspireerd tot nieuwe theorieën en andere vormen van onderzoek. Donald A. Schön en Louis L. Bucciarelli zijn twee exponenten van deze nieuwe benadering, die een alternatief wil bieden voor de traditionele 'rationalistische' modellen en theorieën van de ontwerpmethodologie.
Als introductie tot de dialoog van Schön en Bucciarelli bevat de reader een uittreksel uit het proefschrift van Kees Dorst.

In het vijfde artikel, *Discovering Design Ability,* karakteriseert en verdedigt Cross het ontwerpen als een specifieke activiteit. Het artikel is opgezet als een pleidooi om in technische opleidingen vooral ook het vermogen om te ontwerpen ('design ability') bij studenten te stimuleren. In veel technische opleidingen is dat nog helemaal niet vanzelfsprekend: men heeft de neiging veel theorie te onderwijzen, en gaat er daarbij stilzwijgend vanuit dat het ontwerpen vanzelf wel komt als je alle basiskennis in huis hebt. Cross bouwt zijn pleidooi op aan de hand van een aantal belangrijke vragen:
- Is ontwerpen als activiteit te onderscheiden van andere activiteiten?
- Kun je ontwerpen beschrijven, en kun je het aan iemand leren?
- Kan iedereen ontwerpen? (Is ontwerpen bijzonder?)
- Kun je het vermogen om te ontwerpen ook verliezen?
- Is ontwerpen ook een vorm van intelligentie?

Zijn conclusie is dat ontwerpen inderdaad iets is dat waard is apart en grondig onderwezen te worden. Op basis van zijn antwoorden op de vragen formuleert hij een aantal aanbevelingen voor het ontwikkelen en onderwijzen van het 'ontwerpvermogen' .

2.3 Planning Problems are Wicked Problems

Horst W. J. Rittel and
Melvin M. Webber

A great many barriers keep us from perfecting [an idealized] planning/governing system: theory is inadequate for decent forecasting; our intelligence is insufficient to our tasks; plurality of objectives held by pluralities of politics makes it impossible to pursue unitary aims; and so on. The difficulties attached to rationality are tenacious, and we have so far been unable to get untangled from their web. This is partly because the classical paradigm of science and engineering—the paradigm that has underlain modern professionalism—is not applicable to the problems of open societal systems. One reason the publics have been attacking the social professions, we believe, is that the cognitive and occupational styles of the professions—mimicking the cognitive style of science and the occupational style of engineering—have just not worked on a wide array of social problems. The lay customers are complaining because planners and other professionals have not succeeded in solving the problems they claimed they could solve. We shall want to suggest that the social professions were misled somewhere along the line into assuming they could be applied scientists—that they could solve problems in the ways scientists can solve their sorts of problems. The error has been a serious one.

The kinds of problems that planners deal with—societal problems—are inherently different from the problems that

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scientists and perhaps some classes of engineers deal with. Planning problems are inherently wicked.

As distinguished from problems in the natural sciences, which are definable and separable and may have solutions that are findable, the problems of governmental planning—and especially those of social or policy planning—are ill-defined; and they rely upon elusive political judgment for resolution. (Not 'solution'. Social problems are never solved. At best they are only re-solved—over and over again.) Permit us to draw a cartoon that will help clarify the distinction we intend.

The problems that scientists and engineers have usually focused upon are mostly 'tame' or 'benign' ones. As an example, consider a problem of mathematics, such as solving an equation; or the task of an organic chemist in analyzing the structure of some unknown compound; or that of the chess player attempting to accomplish checkmate in five moves. For each the mission is clear. It is clear, in turn, whether or not the problems have been solved.

Wicked problems, in contrast, have neither of these clarifying traits; and they include nearly all public policy issues—whether the question concerns the location of a freeway, the adjustment of a tax rate, the modification of school curricula, or the confrontation of crime.

There are at least ten distinguishing properties of planning-type problems, i.e. wicked ones, that planners had better be alert to and which we shall comment upon in turn. As you will see, we are calling them 'wicked' not because these properties are themselves ethically deplorable. We use the term 'wicked' in a meaning akin to that of 'malignant' (in contrast to 'benign') or 'vicious' (like a circle) or 'tricky' (like a leprechaun) or 'aggressive' (like a lion, in contrast to the docility of a lamb). We do not mean to personify these properties of social systems by implying malicious intent. But then, you may agree that it becomes morally objectionable for the planner to treat a wicked problem as though it were a tame one, or to tame a wicked problem prematurely, or to refuse to recognize the inherent wickedness of social problems.

1. There is no definitive formulation of a wicked problem

For any given tame problem, an exhaustive formulation can be stated containing all the information the problem-solver needs for understanding and solving the problem—provided he knows his 'art,' of course.

This is not possible with wicked problems. The information needed to *understand* the problem depends upon one's idea for *solving* it. That is to say: in order to *describe* a wicked problem in sufficient detail, one has to develop an exhaustive inventory of all conceivable *solutions* ahead of time. The reason is that every question asking for additional information depends upon the understanding of the problem—and its resolution—at that time. Problem understanding and problem resolution are concomitant to each other. Therefore, in order to anticipate all questions (in order to anticipate all information required for resolution ahead of time), knowledge of all conceivable solutions is required.

Consider, for example, what would be necessary in identifying the nature of the poverty problem. Does poverty mean low income? Yes, in part. But what are the determinants of low income? Is it deficiency of the national and regional economies or is it deficiencies of cognitive and occupational skills within the labour force? If the latter, the problem statement and the problem 'solution' must encompass the educational process. But, then, where within the educational system does the real problem lie? What then might it mean to 'improve the educational system'? Or does the poverty problem reside in deficient physical and mental health? If so, we must add those etiologies to our information package, and search inside the health services for a plausible cause. Does it include cultural deprivation? spatial dislocation? problems of ego identity? deficient political and social skills?—and so on. If we can formulate the problem by tracing it to some sorts of sources—such that we can say, 'Aha! That's the locus of the difficulty', i.e. those are the root causes of the differences between the 'is' and the 'ought to be' conditions—then we have thereby also formulated a solution. To find the problem is thus the same thing as finding the solution; the problem cannot be defined until the solution has been found.

The formulation of a wicked problem *is* the problem! The process of formulating the problem and of conceiving a solution (or re-solution) are identical, since every specification of the problem is a specification of the direction in which a treatment is considered. Thus, if we recognize deficient mental health services as part of the problem, then—trivially enough—'improvement of mental health services' is a specification of solution. If, as the next step, we declare the lack of community centres one deficiency of the mental health services system, then 'procurement of community centres' is the next specification of solution. If it is inadequate treatment within community centres, then improved therapy training of staff may be the locus of solution, and so on.

This property sheds some light on the usefulness of the famed 'systems approach' for treating wicked problems. The classical systems approach of the military and the space programmes is based on the assumption that a planning project can be organized into distinct phases. Every textbook of systems engineering starts with an enumeration of these phases: 'understand the problems or the mission', 'gather information', 'analyse information', 'synthesize information and wait for the creative leap', 'work out solution', or the like. For wicked problems, however, this type of scheme does not work. One cannot understand the problem without knowing about its context; one cannot meaningfully search for information without the orientation of a solution concept; one cannot first understand, then solve. The systems approach 'of the first generation' is inadequate for dealing with wicked problems. Approaches of the 'second generation' should be based on a model of planning as an argumentative process in the course of which an image of the problem and of the solution emerges gradually among the participants, as a product of incessant judgment, subjected to critical argument. The methods of Operations Research play a prominent role in the systems approach of the first generation; they become operational, however, only *after* the most important decisions have already been made, i.e. after the problem has already been tamed.

Take an optimization model. Here the inputs needed include the definition of the solution space, the system of constraints, and the performance measure as a function of the planning and contextual variables. But setting up and constraining the solution space and constructing the measure of performance is the wicked part of the problem. Very likely it is more essential than the remaining steps of searching for a solution which is optimal relative to the measure of performance and constraint system.

2. Wicked problems have no stopping rule

In solving a chess problem or a mathematical equation, the problem-solver knows when he has done his job. There are criteria that tell when *the* or *a* solution has been found.

Not so with planning problems. Because (according to Proposition 1) the process of solving the problem is identical with the process of understanding its nature, because there are no criteria for sufficient understanding, and because there are no ends to the causal chains that link interacting open systems, the would-be planner can always try to do better. Some additional investment of effort might increase the chances of finding a better solution.

The planner terminates work on a wicked problem, not for reasons inherent in the 'logic' of the problem. He stops for considerations that are external to the problem: he runs out of time, or money, or patience. He finally says, 'That's good enough', or 'This is the best I can do within the limitations of the project', or 'I like this solution', etc.

3. Solutions to wicked problems are not true-or-false, but good-or-bad

There are conventionalized criteria for objectively deciding whether the offered solution to an equation, or whether the proposed structural formula of a chemcial compound, is correct or false. They can be independently checked by other qualified persons who are familiar with the established criteria; and the answer will be normally unambiguous.

For wicked planning problems there are no true or false answers. Normally, many parties are equally equipped, interested, and/or entitled to judge the solutions, although none has the power to set formal decision rules to determine correctness. Their judgments are likely to differ widely to accord with their group or personal interests, their special value-sets, and their ideological predilections. Their assessments of proposed solutions are expressed as 'good' or 'bad' or, more likely, as 'better or worse' or 'satisfying' or 'good enough'.

4. There is no immediate and no ultimate test of a solution to a wicked problem

For tame problems one can determine on the spot how good a solution-attempt has been. More accurately, the test of a solution is entirely under the control of the few people who are involved and interested in the problem.

With wicked problems, on the other hand, any solution, after being implemented, will generate waves of consequences over an extended—virtually an unbounded—period of time. Moreover, the next day's consequences of the solution may yield utterly undesirable repercussions which outweigh the intended advantages or the advantages accomplished hitherto. In such cases one would have been better off if the plan had never been carried out.

The full consequences cannot be appraised until the waves of repercussions have completely run out, and we have no way of tracing *all* the waves through *all* the affected lives ahead of time or within a limited time span.

5. Every solution to a wicked problem is a 'one-shot operation'; because there is no opportunity to learn by trial-and-error, every attempt counts significantly

In the sciences, and in fields like mathematics, chess, puzzle-solving, or mechanical engineering design, the problem-solver can try various runs without penalty. Whatever his outcome on these individual experimental runs, it does not matter much to the subject-system or to the course of societal affairs. A lost chess game is seldom consequential for other chess games or for non-chess-players.

With wicked planning problems, however, *every* implemented solution is consequential. It leaves 'traces' that cannot be undone. One cannot build a freeway to see how it works, and then easily correct it after unsatisfactory performance. Large public works are effectively irreversible, and the consequences they generate have long half-lives. Many people's lives will have been irreversibly influenced, and large amounts of money will have been spent—another irreversible act. The same happens with most other large-scale public works and with virtually all public-service programmes. The effects of an experimental curriculum will follow the pupils into their adult lives.

Whenever actions are effectively irreversible and whenever the half-lives of the consequences are long, *every trial counts.* And every attempt to reverse a decision or to correct for the undesired consequences poses another set of wicked problems, which are in turn subject to the same dilemmas.

6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan

There are no criteria which enable one to prove that all solutions to a wicked problem have been identified and considered.

It may happen that *no* solution is found, owing to logical inconsistencies in the 'picture' of the problem. (For example, the problem-solver may arrive at a problem description requiring that both *A* and not-*A* should happen at the same time.) Or it might result from his failing to develop an idea for solution (which does not mean that someone else might be more successful). But normally, in the pursuit of a wicked planning problem, a host of potential solutions arises; and another host is never thought up. It is then a matter of judgment whethere one should try to enlarge the available set or not. And it is, of course, a matter of judgment which of these solutions should be pursued and implemented.

Chess has a finite set of rules, accounting for all situations that can occur. In mathematics the tool chest of operations is also explicit; so, too, although less rigorously, in chemistry.

But not so in the world of social policy. Which strategies-or-moves are permissible in dealing with crime in the streets, for example, have been enumerated nowhere. 'Anything goes', or at least, any new idea for a planning measure may become a serious candidate for a re-solution: What should we do to reduce street crime? Should we disarm the police, as they do in England, since even criminals are less likely to shoot unarmed men? Or reapeal the laws that define crime, such as those that make the use of marijuana a criminal act, or those that make car theft a criminal act? That would reduce crime by changing definitions. Try moral rearmament and subsitute ethical self-control for police and court control? Shoot all criminals and thus reduce the numbers who commit crime? Give away free loot to would-be thieves, and so reduce the incentive to crime? And so on.

In such fields of ill-defined problems and hence ill-definable solutions, the set of feasible plans of action relies on realistic judgment, the capability to appraise 'exotic' ideas and on the amount of trust and credibility between planner and clientele that will lead to the conclusion, 'OK let's try that'.

7. Every wicked problem is essentially unique

Of course, for any two problems at least one distinguishing property can be found (just as any number of properties can be found which they share in common), and each of them is therefore unique in a trivial sense. But by '*essentially* unique' we mean that, despite long lists of similarities between a current problem and a previous one, there always might be an additional distinguishing property that is of overriding importance. Part of the art of dealing with wicked problems is the art of not knowing too early which type of solution to apply.

There are no *classes* of wicked problems in the sense that principles of solution can be developed to fit *all* members of a class. In mathematics there are rules for classifying families of problems—say, of solving a class of equations—whenever a certain, quite-well-specified set of characteristics matches the problem. There are explicit characteristics of tame problems that define similarities among them, in such fashion that the same set of techniques is likely to be effective on all of them.

Despite seeming similarities among wicked problems, one can never be *certain* that the particulars of a problem do not override its commonalities with other problems already dealt with.

The conditions in a city constructing a subway may look similar to the conditions in San Francisco, say; but planners would be ill-advised to transfer the San Francisco solutions directly. Differences in commuter habits or residential patterns may far outweigh similarities in subway layout, downtown layout, and the rest. In the more complex world of social policy planning, every situation is likely to be one-of-a-kind. If we are right about that, the direct transference of the physical-science and engineering thoughtways into social policy might be dysfunctional, i.e. positively harmful. 'Solutions' might be applied to seemingly familar problems which are quite incompatible with them.

8. Every wicked problem can be considered to be a symptom of another problem

Problems can be described as discrepancies between the state of affairs as it is, and the state as it ought to be. The process of resolving the problem starts with the search for causal explanation of the discrepancy. Removal of that cause poses another problem of which the original problem is a 'symptom'. In turn, it can be considered the symptom of still another, 'higher level' problem. Thus 'crime in the streets' can be considered as a symptom of general moral decay, or permissiveness, or deficient opportunity, or wealth, or poverty, or whatever causal explanation you happen to like best. The level at which a problem is settled depends upon the self-confidence of the analyst and cannot be decided on logical grounds. There is nothing like a natural level of a wicked problem. Of course, the higher the level of a problem's formulation, the broader and more general it becomes: and the more difficult it becomes to do something about it. On the other hand, one should not try to cure symptoms: and therefore one should try to settle the problem on as high a level as possible.

Here lies a difficulty with incrementalism, as well. This doctrine advertises a policy of small steps, in the hope of contributing systematically to overall improvement. If, however, the problem is attacked on too low a level (an increment), then success of resolution may result in making things worse, because it may become more difficult to deal with the higher problems. Marginal improvement does not guarantee overall improvement. For example, computerization of an administrative process may result in reduced cost, ease of operation, etc. But at the same time it becomes more difficult to incur structural changes in the organization, because technical perfection reinforces organizational patterns and normally increases the cost of change. The newly acquired power of the controllers of information may then deter later modifications of their roles.

Under these circumstances it is not surprising that the members of an organization tend to see the problems on a level below their own level. If you ask a police chief what the problems of the police are, he is likely to demand better hardware.

9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution

'Crime in the streets' can be explained by not enough police, by too many criminals, by inadequate laws, too many police, cultural deprivation, deficient opportunity, too many guns, phrenologic aberrations, etc. Each of these offers a direction for attacking crime in the streets. Which one is right? There is no rule or procedure to determine the 'correct' explanation or combination of them. The reason is that in dealing with wicked problems there are several more ways of refuting a hypothesis than there are permissible in the sciences.

The mode of dealing with conflicting evidence that is customary in science is as follows: 'Under conditions *C* and assuming the validity of hypothesis *H*, effect *E* must occur. Now, given *C*, *E* does not occur. Consequently *H* is to be refuted.' In the context of wicked problems, however, further modes are admissible: one can deny that the effect *E* has not occurred, or one can explain the non-occurence of *E* by intervening processes without having to abandon *H*. Here is an example: Assume that somebody chooses to explain crime in the streets by 'not enough police'. This is made the basis of a plan, and the size of the police force is increased. Assume further that in the subsequent years there is an increased number of arrests, but an increase of offences at a rate slightly lower than the increase of GNP. Has the effect *E* occurred? Has crime in the streets been reduced by increasing the police force? If the answer is no, several non-scientific explanations may be tried in order to rescue the hypothesis *H* ('Increasing the police force reduces crime in the streets'): 'If we had not increased the number of officers, the increase in crime would have been even greater'; 'This case is an exception from rule *H* because there was an irregular influx of criminal elements'; 'Time is too short to feel the effects yet'; etc. But also the answer 'Yes *E* has occurred' can be defended: 'The number of arrests was increased', etc.

In dealing with wicked problems the modes of reasoning used in the argument are much richer than those permissible in the scientific discourse. Because of the essential uniqueness of the problem (see Proposition 7) and lacking opportunity for rigorous experimentation (see Proposition 5), it is not possible to put *H* to a crucial test.

That is to say, the choice of explanation is arbitrary in the logical sense. In actuality, attitudinal criteria guide the choice. People choose those explanations which are most plausible to them. Somewhat but not much exaggerated, you might say that everybody picks that explanation of a discrepancy which fits his intentions best and which conforms to the action-prospects that are available to him. The analyst's 'world view' is the strongest determining factor in explaining a discrepancy and, therefore, in resolving a wicked problem.

10. The planner has no right to be wrong

As Karl Popper argues in *The Logic of Scientific Discovery*, it is a principle of science that solutions to problems are only hypotheses offered for a refutation. This habit is based on the insight that there are no proofs to hypotheses, only potential refutations. The more a hypothesis withstands numerous attempts at refutation, the better its 'corroboration' is considered to be. Consequently, the scientific community does not blame its members for postulating hypotheses that are later refuted—so long as the author abides by the rules of the game, of course.

In the world of planning and wicked problems no such immunity is tolerated. Here the aim is not to find the truth, but to improve some characteristics of the world where people live. Planners are liable for the consequences of the actions they generate; the effects can matter a great deal to those people that are touched by those actions.

We are thus led to conclude that the problems that planners must deal with are wicked and incorrigible ones, for they defy efforts to delineate their boundaries and to identify their causes, and thus to expose their problematic nature.

3 Descriptions of the design process

The six phases of a design project:
1 Enthusiasm
2 Disillusionment
3 Panic
4 Search for the guilty
5 Punishment of the innocent
6 Praise for the non-participants
Notice on the wall of the Greater London Council Architects Department. (According to Astragal AJ March 22 1978)

"Now for the evidence," said the King, "and then the sentence." "No!" said the Queen, "first the sentence, and then the evidence!" "Nonsense!" cried Alice, so loudly that everybody jumped, "the idea of having the sentence first!"
Lewis Caroll, *Alice Through the Looking Glass*

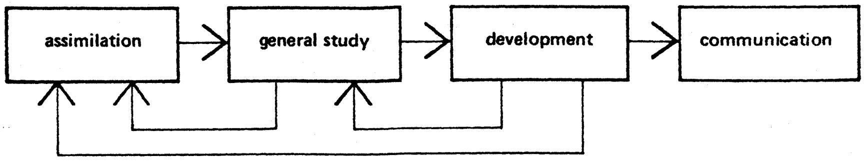
Do we need a definition of design?

This book did not begin with a definition of design but rather with an exploration of the variety and complexity of the designer's role. To attempt a definition of design too soon might easily lead to a narrow and restricted view. To understand fully the nature of design it is necessary not only to seek out the similarities between different design situations but also to recognise the very real differences. Inevitably, each of us will approach this general understanding of design from our own particular background. This is all too apparent when we attempt a comprehensive definition of design. What sort of designer might have offered the following definition? "The optimum solution to the sum of the true needs of a particular set of circumstances." Is it more likely that such a definition is the idea of an engineer or an interior designer? Is it meaningful to talk of "optimum solutions" or "true needs" in connection with interior design? In fact Matchett (1968), who defined design this way, comes from an engineering background. This

definition suggests at least two ways in which design situations can vary. Matchett's use of "optimum" indicates that the results of design as he knows it can be measured against established criteria of success. This may well be the case for the design of a machine where output can be quantified on one or more scales of measurement, but it hardly applies to the design of a stage set or a building interior. Matchett's definition also assumes that all the "true needs" of a circumstance can be listed. More often than not however designers are by no means sure of all the needs of a situation. This is because not all design problems relate to equally purposeful activities. For example, it is much easier to define the needs to be satisfied in a lecture theatre than in a pub. Some pronouncements about design would have us believe that these differences are not really very important. "The process of design is the same whether it deals with the design of a new oil refinery, the construction of a cathedral or the writing of Dante's Divine Comedy" (Gregory 1966). If this were really the case then we might reasonably expect that Dante could have been a successful chemical engineer had he been alive today. Such statements about design, which have been
7 common in recent years, deny the existence of any fundamental differences between the various design fields. The trouble with this approach is that it does not suggest that there is any discovering to be done. It is an intellectual dead end, and further inquiry into the nature of design is rendered unnecessary. Of course it is possible to arrive at a definition of design which allows for both the disparate and the common features. Jones (1970) gives what he regards to be the "ultimate" definition of design: "To initiate change in man-made things." All designers could probably agree that this applies to what they do, but does it really help? Surely such a definition is too general and abstract to be useful in helping us to understand design? Do we really need a simple definition of design or should we accept that design is too complex a matter to be summarised in less than a book? The answer is probably that we shall never really find a single satisfactory definition but that the searching is probably much more important than the finding. At least one well known thinker about design has publicly recognised just how difficult this search is in his description of design as: "The performing of a very complicated act of faith" (Jones 1966).

Some maps of the design process

One way of understanding more about design is to chart a route through the process from beginning to end. There have been many of these maps of the design process and we shall examine some of the most



3.1 The RIBA plan of work map of the design process

frequently used routes in this section. In order to draw such a map we must observe the designer in action. One of the difficulties here is that on the whole there is not a great deal of action to be seen, and what there is cannot easily be understood. True, the designer may sketch or draw profusely but his drawings are by no means totally explicit about what is going on in his head. Unfortunately for those who would wish to draw a map therefore most of the route remains hidden, for it is what goes on in the designer's mind which really matters.

The first map we might examine is that laid out for use by architects in the RIBA practice and management handbook. The handbook tells us that the design process may be divided into four phases:

Phase 1 assimilation

The accumulation and ordering of general information and information specifically related to the problem in hand.

Phase 2 general study

The investigation of the nature of the problem.

The investigation of possible solutions or means of solution.

Phase 3 development

The development and refinement of one or more of the tentative solutions isolated during phase 2.

Phase 4 communication

The communication of one or more solutions to people inside or outside the design team.

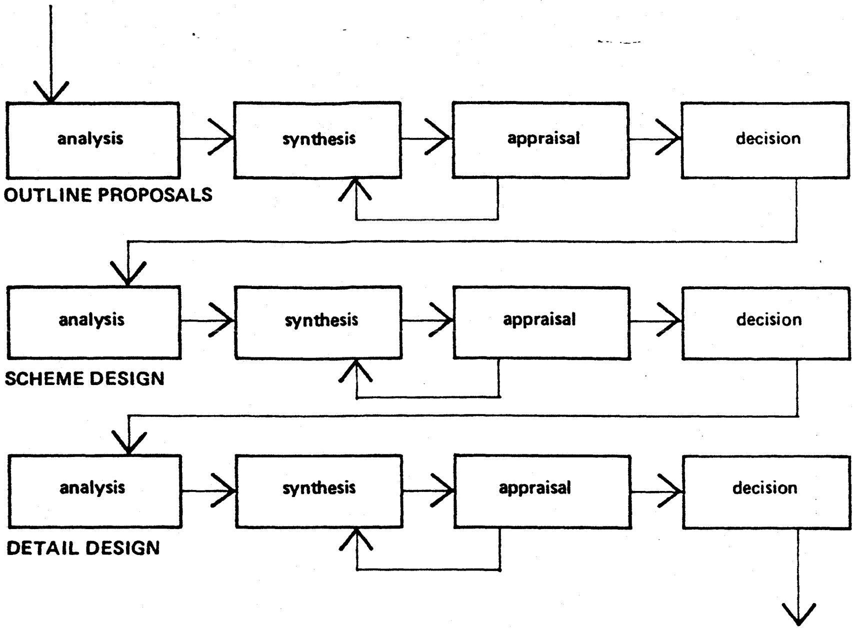
The trouble with this is that it is hardly a map at all. As the handbook points out these four phases are not necessarily sequential although it may seem logical that the overall development of a design will progress from phase 1 to phase 4. Even a cursory logical examination of this map suggests that it is by no means a one way street and that there may have to be much coming and going. For example it is quite difficult to know what information to gather in phase 1 until you have done some investigation of the problem in phase 2. Since the introduction of systematic design methods into design education it has become fashionable to require students to prepare reports accompanying their designs. Frequently such reports contain a great deal of information, slavishly gathered at the beginning of the project, which has no material effect upon the solution. One of the dangers here is that since gathering information is rather less mentally demanding than solving problems there is always a temptation to put off the transition from phase 1 to phase 2. Then again the detailed development of solutions (phase 3) does not always go smoothly and may sometimes suggest that more general study is required (phase 2). In short all this map does is to tell us that designers have to gather information about a problem, study it, devise a solution and draw it, though not necessarily in that order. The RIBA Handbook is very honest here in declaring that there are likely to be unpredictable jumps between the four phases. What it does not tell us is how often or in what way these jumps are made.

If we turn on through the pages of the RIBA Handbook there is yet another, much larger scale map to be found. Because of its immense detail (it occupies 27 A4 pages) this Plan of Work, as it is called, looks much more promising at first sight. The plan of work consists of twelve stages described as a logical course of action.

A	Inception
B	Feasibility
C	Outline proposals
D	Scheme design
E	Detail design
F	Production information
G	Bills of quantities
H	Tender action
J	Project planning
K	Operations on site
L	Completion
M	Feed-back

The handbook rather revealingly also shows a simplified version in what it describes as "usual terminology".

A–B	Briefing
C–D	Sketch plans
E–H	Working Drawings
J–M	Site operations



3.2 The Markus/Maver map of the design process

From this we can see the Plan of Work for what it really is; a description not of the process but of the products of that process. It tells us not how the architect works but rather what he produces in terms of feasibility reports, sketch plans, production drawings, and what he does in terms of obtaining planning approval and supervising the construction of the building. It is also worth noting that the stages in the Plan of Work are closely related to the stages of fee payment in the Conditions of Engagement for Architects. So the Plan of Work may also be seen as part of a business transaction; it tells the client what he will get, and the architect what he must do rather than how it is done. In the detailed description of each section the Plan of Work also describes what each member of the design team (quantity surveyor, engineers etc) will do, and how he will relate to the architect; with the architect clearly portrayed as the manager and leader of this team. This further reveals the Plan of Work to be part of the architectural profession's propaganda exercise to stake a claim as leader of the multi-disciplinary building design team. None of this should be taken as criticism of the RIBA Plan of Work, which probably performs its functions quite adequately, but in the end we probably learn from it more about the role of the RIBA than about the nature of architectural design processes.

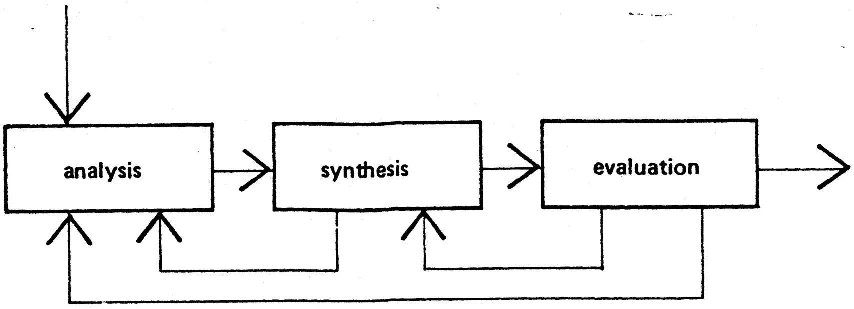
Markus (1969) and subsequently Maver (1970) have developed and related these two RIBA maps of designing. They argue that a complete picture of design method requires both a "decision sequence" and a "design process" or "morphology". Markus and Maver suggest that we need to go through the decision sequence of analysis, synthesis, appraisal, and decision at increasingly detailed levels of the design process (stages 2, 3, 4, 5 in the RIBA Handbook). Since the concepts of analysis, synthesis, and evaluation or appraisal occur frequently in the literature on design methodology it is worth attempting some rough definitions. Analysis involves the exploration of relationships, looking for patterns in the information available, and the classification of objectives. Essentially analysis is the ordering and structuring of the problem. Synthesis on the other hand is characterised by an attempt to move forward and create a response to the problem. Essentially, synthesis is the generating of solutions. Appraisal involves the critical evaluation of suggested solutions against the objectives identified in the analysis phase.

To see how these three functions of analysis, synthesis, and evaluation are related in practice we might examine the thoughts of a chess player deciding on his next move. The procedure suggests that first our player might analyse the current position on the board by studying all the relations between the pieces; the pieces that are being threatened and how, and which of the unoccupied squares remain unguarded.

The next task would be to clarify objectives. Obviously the ultimate long term object of the game is to win, but at this particular stage the priorities between attack or defence and between immediate or eventual gain have to be decided. The synthesis stage would be to suggest a move, which might emerge either as a complete idea or in parts, such as moving a particular piece, occupying a particular square or threatening a particular piece, and so on. This idea then needs evaluating against the objectives.

Our map of the design process must allow for an indefinite number of return loops from evaluation to synthesis. The first move thought of by our chess player may on examination prove unwise or even dangerous, and so it is with design. This accounts for the return loop in the Markus/Maver decision sequence from appraisal to synthesis, which in simple terms calls for the designer to get another idea.

The presence of this return loop in the diagram however raises another question. Why is it the only return loop? Might not the development of a solution suggest more analysis is needed? Even in the

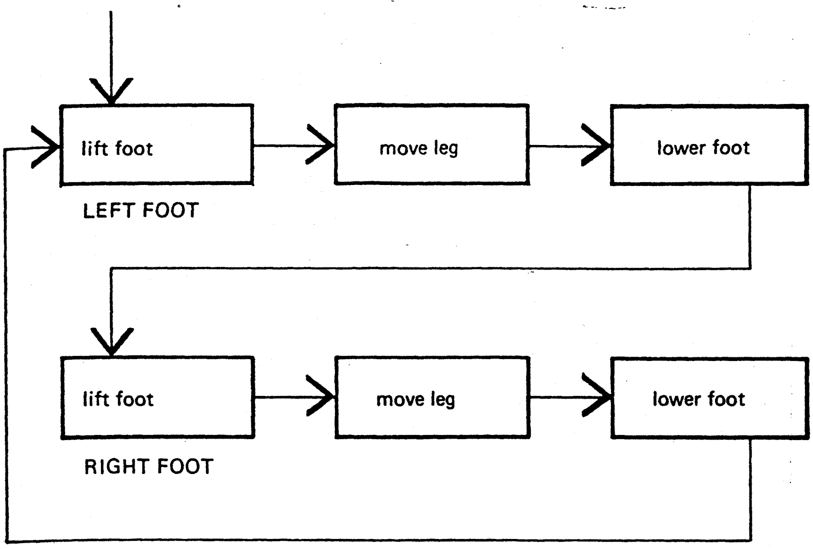


3.3 Even the simplest map of the design process must allow for a return loop to all preceding functions

game of chess a proposed move may reveal a new problem and suggest that the original perception of the state of the game was incomplete and that further analysis is necessary. This is even more frequently the case in design where the problem is not totally described, as on a chess board. This was long ago recognised by Page (1963) who warned the 1962 Conference on Design Methods at Manchester, "In the majority of practical design situations, by the time you have produced this and found out that and made a synthesis, you realise you have forgotten to analyse something else here, and you have to go round the cycle and produce a modified synthesis, and so on." So we are inevitably led to the conclusion that our map should actually show a return loop from each function to all preceding functions.

The map, such as it is, no longer suggests any firm route through the whole process. It rather resembles one of those chaotic party games where the players dash from one room of the house to another simply in order to discover where they must go next. It is about as much help in navigating a designer through his task as a diagram showing how to walk would be to a one year old child. Knowing that design consists of analysis, synthesis and evaluation linked in an iterative cycle will no more enable you to design than knowing the movements of breaststroke will prevent you from sinking in a swimming pool. You will just have to put it all together for yourself.

So much space has been devoted to maps of design because they occur so frequently in the literature. Many writers fail to point out that such maps are probably much more use to the methodologist than to the designer. Indeed they have proved invaluable in provoking a continued study of the design process. At this level of abstraction there is an extraordinarily high degree of agreement between designers in different fields, this suggesting that we are indeed discussing a process which can



3.4 A map of the "walking process" (with apologies to those design methodologists who like maps!)

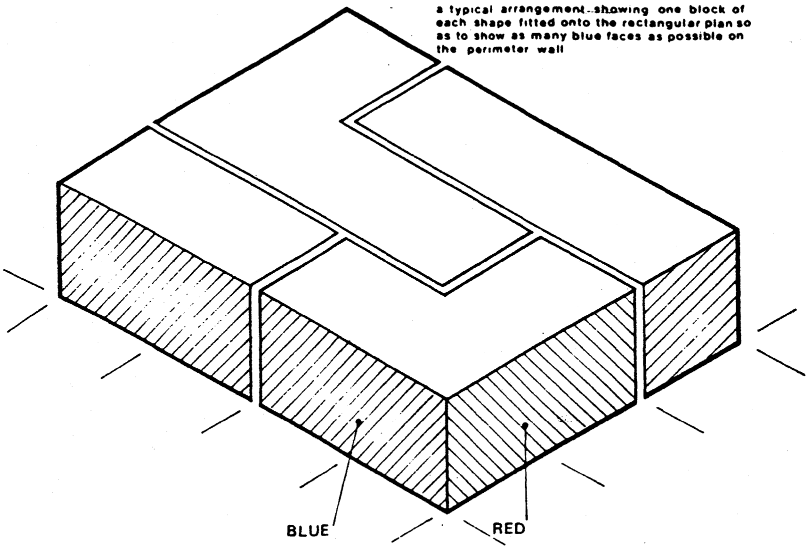
be studied independently of the various technical contexts in which it is practised. Maps of design very similar to those already mentioned have been proposed by engineers (Asimow 1962; and Rosenstein, Rathbone and Schneerer 1964), industrial designers (Archer 1963) and workers in the field of town planning (Levin 1966), as well as by many other architects. In the next section we will see something of how designers actually navigate through the process in practice.

Do we really need to use a map?

We have now seen a few of the many maps of the design process which have been drawn up in recent years by design methodologists. These maps tend to be both theoretical and prescriptive. They seem to have been derived more by thinking about design than by experimentally observing it, and characteristically they are logical and systematic. For example neither the RIBA Handbook nor Markus produce any evidence to show that designers actually behave as if they were reading such maps. We are simply told that this is how design goes as the writers see it. There is a danger with this approach, since writers on design methodology do not necessarily always make the best designers, and that must obviously include this author too. It seems reasonable to suppose that our best designers are more likely to spend their time designing than writing about methodology. In which case we are entitled to ask how valid is a design methodologist's view of the process? Surely he sees design with a rather special perspective? In fact many writers about design have not only trained as designers themselves but are also involved in teaching design. Their thoughts are based not just on their own knowledge of design but also on their experience of observing students struggling to acquire and develop design skills.

There is another way out of this difficulty. In recent years we have begun to study design in a more organised and scientific way. Studies have been and are being conducted in which designers are put under the microscope, and from this research we are gradually learning something of the subtleties of design as it is actually practised. We shall now examine some of this work to see the picture which is gradually emerging.

One of the major questions to be answered here is whether or not designers come to adopt a recognisably consistent approach to design problems. Do all designers use similar strategies or, alternatively, are there as many ways of tackling a problem as there are designers? Lawson (1972) set out to explore this issue in a series of experiments in which various groups, both of designers and non-designers, were asked to solve design-like problems. In one experiment Lawson (1979a) compared the strategies of final year architectural students and science students at a similar stage of post-graduate education. In order not to give the architects a technical advantage an experimental task was devised which did not demand any specialist expertise. In this case the problem was to arrange some modular coloured wooden blocks onto a four by three bay rectangular plan. There were eight blocks, two of each of four different shapes and each with some faces coloured red and some blue. The objective was to so arrange the blocks that either as much red or as much blue as possible was left showing around the external face of the finished design. Only four blocks of the eight, one o each different shape were to be used. In addition, for each problem certain combinations of block were permitted while others were not These allowed combinations were governed by a simple rule which might require one particular block to be present or alternatively at leas one of two specified blocks to be present and so on. While the subject were aware of the existence of this rule they were not told of its nature They were, however, allowed to submit designs and were then tol whether their solutions were acceptable or not. The subject was no given a time limit and was asked to decide for himself when he though he had got the best solution possible and to arrive at this by submittin as few designs as he could.



a typical arrangement showing one block of each shape fitted onto the rectangular plan so as to show as many blue faces as possible on the perimeter wall

3.5 Lawson's (1972) experimental apparatus

Thus this abstract problem is in reality a very simplified design situation where a physical three-dimensional solution has to achieve certain stated performance objectives while obeying a relational structure which is not entirely explicit at the outset. The question was how would the designers and non-designers approach this problem. Would any discernable strategies emerge which might reveal something of the way each group or person was thinking?

The two groups showed quite consistent and strikingly different strategies. Although this problem is simple compared with most real design problems there are still over six thousand possible answers. Clearly then the immediate task facing the subjects was how to narrow this number down and search for an optimal solution. The scientists adopted a technique of trying out a series of designs which used as many different blocks and combinations of blocks as possible as quickly as possible. Thus they tried to maximise the information available to them about the problem. If they could discover the rule governing which combinations of blocks were allowed they could then search for an arrangement which would optimise the required colour around the design.

The architects on the other hand selected their blocks in quite a different way. The eight blocks were examined to see which four blocks had the most of the desired colour, and the first design was built from these four blocks. If this proved not to be an acceptable combination then the next most favourably coloured block would be substituted and so on until an acceptable solution was discovered.

The essential difference between these two strategies is that while the scientists focused their attention on discovering the rule, the architects were obsessed with achieving the desired result. The scientists adopted a generally problem-focused strategy and the architects a solution-focused strategy. Although it would be quite possible using the architects' approach to achieve the best solution without actually discovering the complete range of acceptable solutions, in fact most architects discovered something about the rule governing the allowed combinations of blocks. In other words they learnt about the nature of the problem largely as a result of trying out solutions, whereas the scientists set out specifically to study the problem.

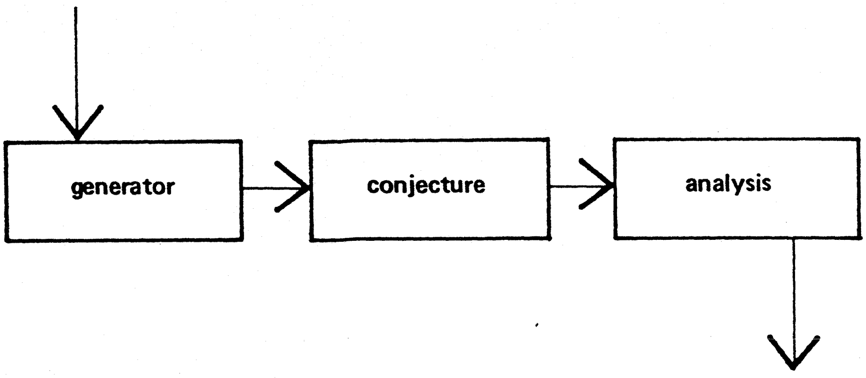
Most of the maps of the design process which we have looked at seem to resemble more closely the non-designer, scientist approach than that of the architects: first analysis and then synthesis. For the designers it seems, analysis, or understanding the problem is much more integrated with synthesis, or generating a solution. Why should this be? Is it that designers are just a different sort of person to scientists, is it the result of their education, or is it something to do with the different nature of the problems they normally solve?

Groups of first year architectural students and sixth year pupils took part in the same experiment. Both groups performed significantly worse than the postgraduate students and neither group showed any consistent problem-solving strategy. The results of these experiments tend to suggest that design students do not naturally have a consistent approach to problems but that they seem to acquire one during their education. It could be argued that the two postgraduate student groups in this experiment had developed strategies that reflected the educational methods they had undergone. An architect is taught mainly by example and practice. He is judged by the solutions he produces rather than the methods by which he arrives at those solutions. Not so the scientist who is taught a succession of concepts and methods of demonstrating the validity of those concepts. He is exercised by examples only in order to demonstrate that he can apply the principles he has learnt. However this is perhaps too simple an explanation. Although their performance was no better overall, both groups of design students showed greater skill than their peers in actually forming the three-dimensional solutions. They appeared to have greater spatial ability and to be more interested in simply playing around with the blocks. Is it then possible that the respective educational systems used for science and architecture simply reinforce an interest in the abstract or the concrete?

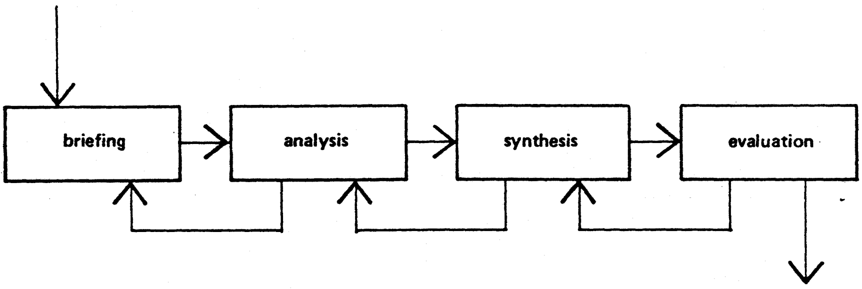
In a slightly more realistic experiment Eastman (1970) asked more experienced designers to redesign a bathroom for speculatively-built houses. Eastman recorded what his designers did and said about what they were doing. From these protocols Eastman showed how the designers explored the problem through a series of attempts to create solutions. There is no meaningful division to be found between analysis and synthesis in these protocols but rather a simultaneous learning about the nature of the problem and the range of possible solutions. The designers were supplied with an existing bathroom design together with some potential clients' criticisms of the apparent waste of space. Thus some parts of the problem, such as the need to reorganise the facilities so as to give a greater feeling of spaciousness and luxury, were quite clearly stated. However the designers discovered much more about the problem as they critically evaluated their own solutions. One of Eastman's protocols shows how a designer came to identify the problem of shielding the toilet from the bath for reasons of privacy. Later this becomes part of a much more subtle requirement as he decides that the client would not like one of his designs which seems deliberately to hide the toilet, the toilet then is to be shielded but not hidden. This requirement was not thought out in the abstract and stated in advance of synthesis but rather discovered as a result of manipulating solutions.

Using a similar approach, Akin (1986) asked architects to design rather more complex buildings than Eastman's bathroom. He observed and recorded the subjects' comments in a series of protocols. In fact, Akin specifically set out to "disaggregate" the design process, or break it down into its constituent parts. Even given this interventionist attack on the problem, Akin failed to identify analysis and synthesis as meaningfully discrete components of design. Akin actually found that his designers were constantly both generating new goals and redefining constraints. Thus, for Akin, analysis is a part of all phases of design and synthesis is found very early in the process.

Darke (1978) has also found this tendency to structure design problems by exploring aspects of possible solutions. She interviewed some well known British architects about their intentions when designing local authority housing. The architects first discussed their views on housing in general and how they saw the problems of designing such housing and then discussed the history of a particular housing scheme in London. In fact the design of housing under these conditions presents an extremely complex problem. The range of legislative and economic controls, the subtle social requirements and the



3.6 Darke's partial map of the design process



3.7 Even the briefing stage needs to be accessible by return loops

demands of London sites all interact to generate a highly constrained situation. Faced with all this complexity Darke shows how the architects tended to latch onto a relatively simple idea very early in the design process. This idea, or primary generator as Darke calls it, may be to create a mews-like street or leave as much open space as possible and so on. For example one architect described how "... we assumed a terrace would be the best way of doing it ... and the whole exercise, formally speaking, was to find a way of making a terrace continuous so that you can use space in the most efficient way ...". Thus a very simple idea is used to narrow down the range of possible solutions, and the designer is then able rapidly to construct and analyse a scheme. Here again we see this very close, perhaps inseparable, relation between analysis and synthesis. Darke however uses her empirically-gained evidence to propose a new kind of map which owes a great deal to another theoretically derived map by Hillier et al (1972). Instead of analysis-synthesis Darke's map reads generator-conjecture-analysis. In plain language, first decide what you think might be an important aspect of the problem, develop a crude design on this basis and examine it to see what else you can discover about the problem.

We shall return to this idea again in a later section but before we leave Darke's work it is worth noting some other evidence that she presents with little comment but which even further calls into question the RIBA Handbook kind of design process map. One of the architects interviewed was explicit about his method of obtaining a design brief (stages A and B in the RIBA Handbook) " ... a brief comes about through essentially an ongoing relationship between what is possible in architecture and what you want to do, and everything you do modifies your idea of what is possible ... you can't start with a brief and (then) design, you have to start designing and briefing simultaneously, because the two activities are completely interrelated." This must also ring very true to any architect who has designed for a committee client, as has the author. One of the most effective ways of making apparent the disparate needs of groups in multi-user buildings such as hospitals is to present the client committee with a sketch design. Indeed clients often seem to find it easier to communicate their wishes by reacting to and criticising a proposed design, than by trying to draw up an abstract comprehensive performance specification.

Further evidence supporting Darke's idea of the primary generator has been collected more recently by Rowe (1987), who actually observed designers in action as opposed to Darke's technique of questioning them afterwards. When reporting one of these case studies in detail, Rowe tells us that "..several distinct lines of reasoning can be identified, often involving the *a priori* use of an organising principle or model to direct the decision making process". These early ideas, primary generators or organising principles sometimes have an influence which stretches throughout the whole design process and is detectable in the solution. However, it is also sometimes the case that designers gradually achieve a sufficiently good understanding of their problem to reject the early thoughts through which their knowledge was gained. Never the less this rejection can be surprisingly difficult to achieve. Rowe records the "tenacity with which designers will cling to major design ideas and themes in the face of what, at times, might seem insurmountable odds". Often these very ideas themselves create difficulties which may be organisational or technical, so it seems on the face of it odd that they are not rejected more readily. However, early anchors can be reassuring and if the designer succeeds in overcoming such difficulties and the original ideas were good, we are quite likely to recognise this as an act of great creativity. For example, Jorn Utzon's famous design for Sydney Opera House was based on geometrical ideas which could only be realised after overcoming considerable technical problems both of struture and cladding. Unfortunately, we are not all as creative as Utzon, and it is frequently the case that design students create more problems than they solve by selecting impractical or inappropriate primary generators.

This discussion has oversimplified reality by implicity suggesting that primary generators are always to be found in the singular. In fact, as Rowe points out, it is the reconciling and resolving of two or more such ideas which characterises design protocols. However we must leave further discussion of this complication, and of the rejecting or resolving of primary generators, until a later chapter.

Problem Forming, Problem Finding, and Problem Solving in Design

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This meeting [1], representing a convergence of students of design from a range of wholly dissimilar disciplines, is an event of major significance. It is significant that the meeting is being held at all — that all of you recognize your common concerns. It is significant that we are gaining deep insights into the design process itself. If it is pretentious to talk about the "science of design," at least we know now that there are truths about design that can be formulated and communicated, general truths that seem to apply to design as each of us knows it, in his or her particular professional domain.

But perhaps it is not really pretentious to speak of the science of design. There are principles that are widely applicable, and increasingly, we are finding ways of implementing these principles on electronic computers, and thereby securing the powerful assistance of those computers in the process of design. Let's compromise on "the art and science of design."

In recent years, the awareness of our communalities, whatever the specific field in which we work, has been hastened by the applications of computers to design: expert systems, computer aided design, artificial intelligence. Because their programs are open to inspection, computers allow us to look at the design process. The program is a tangible, concrete object. And in order to construct programs to design or assist design, we have to try to understand the process. That process is basically the same, whether it is carried out by people or computers, or, as is increasingly the case, by both in collaboration.

1. Some Terminology

Design, as I am using the term, means synthesis. It means conceiving of objects, of processes, of ideas for accomplishing goals, and showing how these objects, processes, or ideas can be realized. Design is the complement of analysis — for analysis means understanding the properties and implications of an object, process, or idea that has already been conceived.

In analysis, the final design is given, and the question to be answered is: what are its properties and how will it behave? In design, the goals and constraints, at most, are given, and the question to be answered is: what design or designs will satisfy these goals and constraints? Seldom will the goals and constraints be satisfied by only a single, unique design; and seldom will it be feasible to examine all possible designs to decide which one is, in some sense, optimal. Designing is satisficing, finding an acceptable solution.

2. Choice as a Component of Design

One component of design is choice — the selection of one from among a number of available alternatives. We have many powerful analytic tools to aid choice — the tools forged by economics, by statistical decision theory, and by operations research. Almost all of these tools fit the following general paradigm: we are given a set of objectives and constraints; we are also given a set of alternatives to choose from. Finally, we are given rather complete information (although it may be probabilistic) about the goal level (utility) that each alternative will attain.

If the problem is not too complex, so that the computation of the optimum is feasible, the analytic procedure will announce to us the optimal choice. We need to emphasize the condition, "if the problem is not too complex." In most real-world situations, the problem is, indeed, too complex, and drastic approximations must be made in the description of reality before it is computationally feasible to make "optimal" choices — i.e., choices that would be optimal if the approximate world were the real world. Fortunately, choices that are optimal in the approximate world are frequently satisfactory in the real world.

3. Finding or Generating Alternatives

However, I do not wish to dwell upon the choice aspect of design, for it is not the aspect on which designers spend most of their time and energy. Most design resources go into discovering or generating alternatives, and not into choosing among them. in fact, it is quite common for a single alternative to emerge from the design process — a single plan for a house, or for a bridge, or a single score for a sonata. No choice remains; all of the choosing has been done in the course of generating, selecting among, and combining the elements and components of the design. Choice is thoroughly intermingled with generation.

The elements of a design are not, of course, made from whole cloth. The designer begins with some primitives — some components that he or she knows are available or can be produced. Design is a game of combinatorics played on these primitives. We should not be surprised that, however banal the primitives, novelty — even admirable novelty — can emerge out of this combinatorial process. After all, 92 natural elements suffice, by combinatorics, to produce all the substances that are found in nature or created by human artifice. Four nucleotides in DNA suffice to encode the 20 amino acids; and these 20 amino acids construct the innumerable proteins of living matter. Darwin's combinatorial game, played on the four nucleotides accounts for all of living nature. Combinatorics is the very heart of creation, hence of design.

However much selection among partial and component alternatives take place in the course of the design process, I want to stress the radical difference between choosing among alternatives and generating alternatives. There is no place in choice for the designer's surprise at the unexpected novelties he or she creates by combining and recombining the primitives. In domains of scientific, artistic, or technical interest, the designer cannot foretell — until quite late in the game — what will emerge. (Else what need for the arduous process of design?)

Design is inherently computational — a matter of computing the implications of initial assumptions and combinations of them. An omniscient God has no need to design: the outcome is known before the process starts. To design is to gather information about what follows from what one has proposed or assumed. It is of interest only to creatures of limited information and limited computing power — creatures of bounded rationality like ourselves.

4. The Focus of Attention

There are three ways, all critical for the process of design, in which our rationality is bounded. I have already alluded to the first two: we know only an infinitesimal fraction of the things we need to know — the things that are relevant for arriving at an optimal design. And our computational powers allow us to compute only a few of the innumerable implications of the things we do know.

But our rationality is also bounded in a third way. We store what we know in that encyclopedic portion of the brain that is usually called "long-term memory." Other parts of our knowledge we store in external encyclopedias and reference sources, traditionally on paper but increasingly in computer memories, only the index to the information being held in memory. The long-term memory, too, is indexed, and is accessed by the process we call recognition. Some stimulus in the external environment — a word on a page, a picture, an object — gives us access to information already stored in memory about that kind of word, picture, or object. We say that we recognize it.

Now this method of information storage imposes severe limits on us. We can only recover the information that is indexed and that is cued by recognition. And we can only look at one page of the encyclopedia at a time. We may have a vast amount of information potentially at our disposal, but only a small fragment of it — whether stored internally or externally — can be in our focus of attention at any one moment.

Our small attention capacity is dramatized by George Miller's "Magical Number Seven." Short-term memory, the memory of attention, can hold only about seven familiar "chunks." You can easily test that. Look up a phone number in the directory and retain it until you can dial it. Most of us can do that, unless interrupted. Now try it with two phone numbers, holding one while you dial the other. I think you will fail.

As designers, we know that we must augment our short-term memories with external memory aids. Historically, the most important of these is the drawing on a drawing board. Today, a computer screen often replaces the drawing board. As relevant information is retrieved or generated, we enter it on our drawing, and thereby accumulate a richer store of information about our current problem. But even the drawing provides only a partial answer to the problem of limited attention. As the amount of information in the drawing increases, we find that we can no longer attend to all of it simultaneously, only to a few chunks. So the problem of information retrieval is simply transferred from short-term and long-term memory to the drawing. The problem is still there, and the momentary focus of our attention is still limited.

In the remainder of my talk, I will respond to our own limits of attention by focusing upon the magical number seven and the drawing board as major determinants of the design process —

determinants that exert a major influence on design goals and on the form that design problems take. This will give us only a partial view of design; but when complex matters are under discussion, partial views are all we can have. That is, in fact, the moral of my story.

5. The Drawing Board

The drawing board, I have said, accumulates information. We attend to one aspect of the design task, make a decision, record it in the drawing. It remains there, combining with and relating to all of the other decisions that we have made and will make. To use the information in the drawing, we have to attend to it selectively, responding to our current goals and the cues we can see.

But the drawing does more than record and cumulate information. It also makes inferences for us, inferences that would be difficult or almost impossible to make without it (or without a corresponding picture in our mind's eye). Let me illustrate with a trivial example, simple enough that we can do it in our heads, without a drawing. I ask you to image a rectangle, twice as wide as it is high. I ask you to drop a vertical line from the middle of the top side of the rectangle to the bottom side. Now your mind's eye performs some marvelous calculations for you. I ask you what the shape is of the two figures into which the rectangle has been divided. Without hesitation, you reply, "They are squares, of course." Would you know that, and could you prove that, without the mental image or a drawing?

Let me carry the example one step further. I draw a diagonal from the northwest corner to the southeast corner of the rectangle. Does the diagonal intersect the vertical line you drew (or imaged) previously? Of course it does. How do you know? You can "see" the point of intersection. Thus, the drawing, or mental image, creates new objects (e.g., points) and relations between objects (e.g., intersections of lines) that would be exceedingly hard to generate if you had to infer them by logical or mathematical reasoning. A drawing, in addition to being a store of information, is a quite powerful inference engine (Larkin and Simon, 1987). We make a series of choices, which we record on the drawing; the drawing effortlessly "calculates" many of the consequences of the interaction of these choices.

There are, of course, serious limits on the inferences that drawings make for us. An important contribution of CAD has been to remove the particular limit imposed by the two dimensionality of the drawing. The computer can store images in three dimensions (or more), and when necessary, can display them in ways that make the three-dimensionality evident. And even without the display, it can calculate whether objects intersect in three dimensions or pass in front of or behind each other.

The ability to cumulate information in drawings and to make many inferences, automatically, about interrelations exerts a dominant influence on the organization of the design process wherever drawings can be used. Now the designer is no longer faced with the impossible task of attending to everything at once. A design decision, based on specialized considerations, can be recorded, and subsequently it can be reviewed from viewpoints quite different from the one that generated it.

While a drawing is being scanned at any stage of the design process, cues may evoke relevant information — about details to be attended to, about constraints that have been violated, about alternatives that haven't been considered — information that was outside the focus of attention when previous decisions were made. Repeated applications of this recognition mechanism can guarantee that the final design product will be responsive to a vast range of considerations that couldn't possibly have been held in attention simultaneously.

Of course the choose-record-review-recognize-revise cycle can be applied to any system of accumulating information. It need not be a drawing. However, our eyes are marvelously adapted to scanning drawings and other visual scenes, and to noticing a wide variety of cues in them. In addition, as we have observed, drawing is also a powerful inferential process. For these reasons, we make great use of drawings whenever we are designing systems that are disposed in space, and sometimes even when we are designing more abstract objects. For we go to great pains to find ways to represent even our abstractions in drawings: for examples, computer programs and other temporal processes in flow diagrams; or the steam cycle in thermodynamics.

6. Goals in Design

Designing anything that is the least bit complex (and if it weren't complex, we wouldn't be considering it here) calls for weighing and balancing a whole host of considerations. In designing a house, we have to consider the control of temperature, the view from the windows, the shapes of rooms and doors, fenestration, room arrangement — I can't begin to enumerate all of the considerations that go into the criterion function for a house.

In designing something as simple as an electric motor, we have to make sure that it delivers the desired amount of power, using the right amount of current at the right voltage. It must be designed so that it will not overheat. (An employer once complained to me — he was objecting to the specialization of engineering education — that he had to hire two engineers to design a motor: one to do the electrical circuit, the other to make sure the motor wouldn't burn up.) It must be made of materials that are as cheap as possible, and it should be as easily machined and manufactured as possible.

Similar lists of desiderata that must be attended to could be drawn up for designing organizations, high school curricula, advertising campaigns, or anything else you might want to consider. The criterion function, or the combination of criteria and constraints, is invariably elaborate — much more than we can keep in mind at one time.

In fact, it is misleading to speak of a "criterion function," for that phrase conjures up a picture of a neat synthesis of all the disparate criteria and constraints into some kind of weighted average — a utility, a magical number that sums up our evaluation of the design in terms of all of our combined desires, and needs. There is no such synthesis. We evaluate design products by applying a whole host of discrete criteria and constraints. When some of them are satisfied and some fail, we modify both the design and the criteria and constraints. When we reach a point where we are no longer certain whether the trade-offs are producing a net gain or a net loss — where we are not even sure we know how to compare them — we are usually ready to settle for the result. We look for a design that meets each of our goals and constraints at some level that expresses the aspiration we have formed along that dimension.

7. The Design Satisfices

If this is the way in which we evaluate our designs, then it follows that we don't have to have all of our criteria in mind at once. In particular, we don't have to have all the criteria in mind when we begin the design process. We can count on recognition processes to evoke considerations we had not earlier attended to, and thereby to guarantee we will not neglect them permanently. Not only do alternatives emerge in the course of the design process, but the design goals — the criteria and constraints to be satisfied — emerge also. The design problem is continually reformulated during the process of design. Design is a process of forming, finding, and solving problems. Nor does the forming and finding always come first, followed by the solving. All three subprocesses are thoroughly intermingled.

8. The Emergence of Goals

At this point you may wish to protest that I am playing verbal games. Goals do not really emerge, you object, in the process of design. The goals are really there all along. It is just that they are not all being attended to at the outset; they are stored in long-term memory (or in reference sources) to be accessed and responded to when the appropriate time comes.

This objection misses, I believe, the main lesson of bounded rationality. In human activity it is not what we know "in principle" that counts, but what we know with awareness, here and now. Let me propose a simple example. Suppose that you are offered a papaya, something you have never tasted. What is the goal function that will determine your response? Clearly the utility of papaya taste can't be a part of it, because you don't know what that is. You will have to respond in terms of some kind of "value of new experiences," which has nothing, directly, to do with papayas. Your first bite will evoke a new dimension of utility — the actual taste you experience. It will probably influence whether you take a second.

Now with sufficient ingenuity you can construct a utility function that will accommodate this example. It contains desire for new experiences as well as utilities for various dimensions and combinations of dimensions of taste. With such a function, first and second bites could have quite different utilities. But I submit that such a construction is pure artifice. It is much more useful to describe the situation by saying that having tasted a papaya and liked it, you have formed the new goal of eating a papaya from time to time — especially when one is offered to you. In particular, the taste of the papaya played no part in the decision to take the first bite, and could be omitted from the initial criterion function. After that bite, the criterion function changed.

If you will accept this latter way of viewing the situation, we can draw some consequences from it for the design process. There are two sources of knowledge that, not initially attended to, can be brought into the process. The one source is memory: knowledge is evoked in the course of the process that was not considered at the outset. The other source is nature: in the course of the process, we may learn things that we did not know before, or experience things we had not experienced before, and that learning or experience may change our preferences.

On both counts, we cannot really regard the goals of design as given any more than we regard the alternatives as given. A design process begins with some criteria and some possibilities (or primitives out of which alternatives can be constructed). As the process goes forward, new criteria and new possibilities are continually being evoked from the sources we have identified.

By designing — exploring — we learn what we can have; but we also learn what we want.

9. Sequence in Design

We do not start designing wholly innocent of goals and constraints. We start with initial goals that guide the first steps of the design process. These initial goals are soon augmented with others that are evoked as the process goes forward.

The sequence in which goals are generated is not insignificant, for different sequences will produce different final designs. (In my paper on *Style in Design*, I have argued that the order in which things are taken up in the design process is a major determinant of what we usually call "style.") The goals and constraints we postulate at the beginning represent commitments that limit the alternatives we can generate. Many possible designs will be ruled out by these initial commitments.

In choosing the sequence in which goals will be introduced, designers are guided by a number of heuristics, some of which are specific to particular domains of design, but others of which are quite general. For example, a basic heuristic is to include the most important goals and constraints among those postulated initially. Designing a house starts with criteria that govern the siting and floorplan, not the bathroom plumbing. Failing to include important criteria in the initial problem formulation can lead the designer into blind alleys from which there is no recovery without starting over.

A second heuristic is to put aggregate criteria first, before attending to criteria that govern specifics. In designing a building, it is usually advantageous to specify total cost and volume before siting and floor plan are considered.

A third heuristic is to postulate first those criteria that are the most restrictive, for restrictions will reduce the combinatoric explosion of possibilities, hence will keep the design task within manageable compass. Human beings often do their best designing when they are faced with severe constraints, for then they are protected against the disorganization and aimlessness that an excess of possibilities can induce. The Gothic cathedral builders were not disadvantaged by the difficulties of being limited to building by placing stone on stone. On the contrary, dealing with these difficulties produced some of the essential beauties of these structures.

There is another side to the discipline of constraints, however. If initial constraints are too rigid, many possible directions of development will be closed off, and there will be little opportunity for goals not included in the initial set to have much influence on the final design. Goals will have little chance to be modified by experience.

I should like to take up this need for flexibility as my final topic. But in concluding this section, I must state once more its basic theme: Determining the sequence in which goals and constraints are to be considered is a major step in designing, and a major determinant of the style of the design product.

10. Designing for Flexibility

Because human rationality is severely bounded, all thinking works with highly incomplete models of the problem situation. The antidote to this incurable tunnel vision is to retain flexibility, so that when a problem is later examined from a new viewpoint, decisions taken previously can be modified. Commitments must be tentative. Without such flexibility, constraints cannot be applied sequentially.

We usually think of flexibility, not as a characteristic of the design process but of the design product. We think of flexibility as designing something that will be adaptive to future, and presently unanticipated, conditions that are different from the conditions at the time the design is made. But we have seen that the design process is itself a temporal flow, a continuous sequence of decisions with a past, a present, and a future.

Flexibility in the design process allows new knowledge to be used whenever it emerges, early or late. Equally, flexibility allows response to new criteria whenever they are evoked. It permits goals to be modified and augmented, new constraints to be introduced. What we usually regard as the design process — the steps taken up to the point where we have created a design to be realized — is just the first stage of a longer process. First we design a building; then we use it — that is, we continually redesign it.

The role of flexibility in these two stages is essentially the same. We need flexibility throughout the design process so that the design can evolve, responding to new considerations at each stage. We need flexibility in the design product so that it can continue to evolve in use, responding to new needs and new conditions. In short, we need flexibility because our bounded rationality is unable to anticipate all of the contingencies that will arise during the process of design or all those that will arise when we later use the designed object.

The need for flexibility is implicit in all design, but flexibility may also be an explicit design goal. For example, when we design a computer language we anticipate only in a statistical sense, or even more vaguely than that, what programs we will want to write in it.

When we design a computer language for writing artificial intelligence programs, the need for deliberate flexibility becomes even greater. Artificial intelligence uses heuristic search, and heuristic search seeks problem solutions along paths that cannot be anticipated. Computer memory must be organized so that structures of arbitrary size and conformation can be stored, accessed, and modified in arbitrary ways. So the most striking characteristic of AI languages like LISP is that they support this flexibility in memory organization — that they do so was the central specification in their design.

11. Design of Social Systems

The criterion of flexibility also takes on special significance in the design of objects that are intended to have long lives — such objects as buildings, cities, and institutions.

A city plan can hardly be regarded as more than a pointer to some initial steps that will urge subsequent development in a particular direction. When Pittsburgh, in the early 1950s, cleared its Golden Triangle, this initiated a sequence of events, most of them then unanticipated, that redeveloped the center of the city around its dramatic setting at the meeting of two rivers. The particular configuration of buildings we see today is a response to that first initiative, but is grossly different from the configuration that appeared on the 1950s drawings. We can think of the whole thirty five year period as a design exercise carried out, not on a drawing board but on the site of the city itself. There is no clear boundary between design and action. Each stage of thought or action is merely a starting point for the next thought or action.

Nor should it be supposed that the design goals were fully specified in the original plans. As the new city emerges, we examine it. We live in it and experience its qualities. It changes our values and our aspirations. We have new conceptions of what a city is.

Designs for organizations have the same tentative and emerging quality. My favorite example is of the same vintage as the Pittsburgh plan: the Economic Cooperation Administration (ECA), established in 1948 to manage the Marshall Plan Aid that we offered to ensure European economic recovery after World War II. The goal of the legislation was to provide the European nations with funds and goods that would enable them to revive their own productive capacities. But there were many different ways in which an organization could have been structured to do that.

The ECA could have been an organization for processing European shopping lists, validating them, and aiding procurement. That was one model. Another conceived the ECA as an extension of the State Department, organized to engage in bilateral negotiations with individual nations to fix the terms on which aid would be offered. A third model — the one followed — conceived the organization as a nucleus around which economic cooperation among the European states could develop, so that they would be led toward a European economy very different from the fragmentation of the pre-War era.

The means for achieving this longer-range goal was to establish a strong Paris office of the ECA, and to give that office a large measure of authority for negotiating with a counterpart organization of European states. Today's European Economic Community is the direct product of this decision, although it was certainly not anticipated in anything like its present form. The organization plan did not mastermind the future; but it surely did push events in a particular direction.

These two examples, one of a city, the other of international organization, reveal to us a criterion that is central in virtually all social planning, a particular form of the criterion of flexibility. Since designing a social system is an unending process, we cannot design specific configurations. We can only design for a "steady state," a continuous flow of events that will maintain a satisfactory present while preserving the potential for satisfactory futures. The guiding principle of such design is that every generation should be guaranteed as wide a range of options as was available to the generation that preceded it.

12. Conclusion

The design process is shaped in fundamental ways by the fact that human rationality is bounded, and shaped especially by the very narrow focus of human attention. Computers enable us to handle a little more information than we could before, and computer a few more of the implications of our knowledge. But they do not change the basic fact of bounded rationality. With or without computers, we can take into account at one time only a tiny bit of the real world's complexity.

It follows that design is a process of search, and of the discovery of new information about alternatives that are available and about the consequences that will follow if those alternatives are chosen. But design is also a process for discovering the goals to be achieved and the constraints to be satisfied. Goals and constraints are no more fixed elements in design than is anything else.

Design is always tentative. At every point of time, the design is subject to revision. And to the end of the life of the designed object, that object and its uses are subject to revision. A major goal at each step of the design process is to realize goals while keeping options for the future open.

Design needs to be approached with a modesty about our ability to anticipate the future, much less to control it wisely. Good design decides on goals and chooses alternatives without preempting the choices of goals that our successors may wish to make.

Note

[1] This lecture was delivered to the First International Congress on Planning and Design Theory, Boston, 1987.

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7 Problems and solutions

Design problems and design solutions are inexorably interdependent. It is obviously meaningless to study solutions without reference to problems and the reverse is equally fruitless. The more one tries to isolate and study design problems the more important it becomes to refer to design solutions. In design, problems may suggest certain features of solutions but these solutions in turn create new and different problems. In chapter 3 we looked at simple definitions of design and concluded that such a complex process defied simple description. In the succeeding chapters we have explored the nature of design problems, frequently finding ourselves simultaneously involved in a discussion of solutions. It is worth pausing briefly here to summarize some of the important characteristics of design problems and solutions and the lessons that can be learnt about the nature of the design process itself. The following points should not be taken to represent a comprehensive list of discrete properties of the design situation; indeed they are often closely interrelated and there is thus some repetition. Taken together, however, they sketch an overall picture of the nature of design as it seems today.

Design problems

1 Design problems cannot be comprehensively stated
As we saw in chapter 3 one of the difficulties in developing a map of the design process is that it is never possible to be sure when all aspects of the problem have emerged. In chapter 6 we saw how design problems are generated by several groups or individuals with varying degrees of involvement in the decision making process. It is clear that many components of design problems cannot be expected to emerge until some attempt has been made at generating solutions. Indeed many features of design problems may never be fully uncovered and made explicit. Design problems are often full of uncertainties both about the objectives and their relative priorities. In fact both objectives and priorities are quite likely to change during the design process as the solution implications begin to emerge. Thus we should not expect a comprehensive and static formulation of design problems but rather they should be seen as in dynamic tension with design solutions.

2 Design problems require subjective interpretation
In the introductory first chapter we saw how designers from different fields could suggest different solutions to the same problem of what to do about railway catering not making a profit. In fact not only are designers likely to devise different solutions but they also perceive problems differently. Our understanding of design problems and the information needed to solve them depends to a certain extent upon our ideas for solving them. Thus because an industrial designer can see how to redesign the train he sees problems in the way buffet cars are laid out, while the operations researcher sees deficiences in the timetabling and scheduling of services and the graphic designer identifies inadequacies in the way the food is marketed and presented.

As we saw in chapter 5 there are many difficulties with measurement in design and problems are inevitably value-laden. In this sense design problems, like their solutions, remain a matter of subjective perception. What may seem important to one client or user or designer may not seem so to others. We should therefore not expect entirely objective formulations of design problems.

3 Design problems tend to be organised hierarchically
In chapter 4 we explored how design problems can often be viewed as symptoms of other higher-level problems illustrated by Eberhard's (1970) tale of how the problem of redesigning a doorknob was transformed into considerations of doors, walls, buildings and eventually organisations. Similarly the problem of providing an urban playground for children who roam the streets could be viewed as resulting from the design of the housing in which those children live, or the planning policy which allows vast areas of housing to be built away from natural social foci, or it could be viewed as a symptom of our educational system, or the patterns of employment of their parents. There is no objective or logical way of determining the right level on which to tackle such problems. The decision remains largely a pragmatic one; it depends on the power, time and resources available to the designer, but it does seem sensible to begin at as high a level as is reasonable and practicable.

Design solutions

1 There are an inexhaustible number of different solutions
Since design problems cannot be comprehensively stated it follows that there can never be an exhaustive list of all the possible solutions to such problems. Some of the engineering-based writers on design methodology talk of mapping out the range of possible solutions. Such a

notion must obviously depend upon the assumption that the problem can be clearly and unequivocally stated, as implied by Alexander's method (see chapter 5). If however we accept the contrary viewpoint expressed here, that design problems are rather more inscrutable and ill-defined then it seems unreasonable to expect that we can be sure that all the solutions to a problem have been identified.

2 There are no optimal solutions to design problems

Design almost invariably involves compromise. Sometimes stated objectives may be in direct conflict with each other, as when motorists demand both good acceleration and low petrol consumption. Rarely can the designer simply optimise one requirement without suffering some losses elsewhere. Just how the trade-offs and compromises are made remains a matter of skilled judgement. There are thus no optimal solutions to design problems but rather a whole range of acceptable solutions (if only the designers can think of them) each likely to prove more or less satisfactory in different ways and to different clients or users. Just as the making of design decisions remains a matter of judgement so does the appraisal and evaluation of solutions. There are no established methods for deciding just how good or bad solutions are, and the best test of most design is still to wait and see how well it works in practice. Design solutions can never be perfect and are often more easily criticised than created, and designers must accept that they will almost invariably appear wrong in some ways to some people.

The Design process

1 The process is endless

Since design problems defy comprehensive description and offer an inexhaustible number of solutions the design process cannot have a finite and identifiable end. The designer's job is never really done, and he can always try to do better. In this sense designing is quite unlike puzzling. The solver of puzzles such as crosswords or mathematical problems knows when he has finished and can often recognise a correct answer, but not so the designer. The designer identifies the end of his process as a matter of judgement. It no longer seems worth the effort of going further because the chances of significantly improving on the solution seem small. This does not mean that the designer is necessarily pleased with his solution, but perhaps unsatisfactory as it might be it represents the best that he feels can be done. Time, money and information are often major limiting factors in design and a shortage of any of these essential resources can result in what the designer may feel to be a frustratingly early end to the design process. Some designers of large and complex systems involving long time scales are now beginning to view design as a continuous and continuing, rather than a once and for all process. Perhaps one day we may get truly community-based architects for example who live in an area constantly servicing the built environment as doctors tend their patients.

2 There is no infallibly correct process

Much though some early writers on design methodology may have wished it, there is no infallibly good way of designing. In design the solution is not just the logical outcome of the problem, and there is therefore no sequence of operations which will guarantee a result. The situation, however, is not quite as hopeless as this statement may suggest. We saw in chapter 6 how it is possible to analyse the structure of design problems and in the next section we shall explore the way designers can and do modify their process in response to this variable problem structure. In fact we shall see how controlling and varying the design process is one of the most important skills a designer must develop.

3 The process involves finding as well as solving problems

It is clear from our analysis of the nature of design problems that the designer must inevitably expend considerable energy in identifying the problems confronting him. It is central to modern thinking about design that problems and solutions are seen as emerging together rather than one following logically upon the other. The process is thus less linear than implied by many of the maps discussed in chapter 3 but rather more argumentative. That is, both problem and solution become clearer as the process goes on. We have also seen in chapter 6 how the designer himself is actually expected to contribute problems as well as solutions. Since neither finding problems nor producing solutions can be seen as predominantly logical activities we must expect the design process to demand the highest levels of creative thinking. We shall discuss creativity as a phenomenon and how it may be promoted in the next section.

4 Design inevitably involves subjective value judgement

Questions about which are the most important problems, and which solutions most successfully resolve those problems are often value-laden. Answers to such questions, which designers must give, are therefore frequently subjective. As we saw in the discussion of the Third London Airport in chapter 5, how important it is to preserve churches or birdlife or to avoid noise annoyance depends rather on your point of view. However hard the proponents of quantification, in this case in the form of cost benefit analysis, may argue they will never convince ordinary people that such issues can rightly be decided entirely objectively. Complete objectivity demands dispassionate detachment. Designers being human beings find it hard to remain either dispassionate or detached about their work. Indeed designers are often aggressively defensive and possessive about their solutions. Perhaps it was this issue above all else that gave rise to the first generation of design methods; designers were seen to be heavily involved in issues about which they were making subjective value judgements. However this concern cannot be resolved simply by denying the subjective nature of much judgement in design. Perhaps current thinking tends more towards making the designer's decisions and value judgements more explicit and allowing others to participate in the process, but this path too is fraught with many difficulties.

5 Design is a prescriptive activity

One of the popular models for the design process to be found in the literature on design methodology is that of scientific method. Problems of science however do not fit the description of design problems outlined above, and consequently the processes of science and design cannot usefully be considered as analogous. The most important, obvious, and fundamental difference is that design is essentially prescriptive whereas science is predominantly descriptive. Designers do not aim to deal with questions of what is, how and why, but rather with what might be, could be and should be. While scientists may help us to understand the present and predict the future, designers may be seen to prescribe and to create the future, and thus their process deserves not just ethical but also moral scrutiny.

6 Designers work in the context of a need for action

Design is not an end in itself. The whole point of the design process is that it will result in some action to change the environment in some way, whether that be by the formulation of policies or the construction of buildings. Decisions cannot be avoided or even delayed without the likelihood of unfortunate consequences. Unlike the artist, the designer is not free to concentrate exclusively on those issues which seem most interesting. Clearly one of the central skills in design is the ability rapidly to become fascinated by problems previously unheard of. We shall discuss this difficult skill in the next section.

Not only must the designer face up to all the problems which emerge he must also do so in a limited time. Unlike the scientist, the designer is often not free to decide that he needs more information, rather he must get on and make the best of a bad job. Design is often a matter of compromise decisions made on the basis of inadequate information. Unfortunately for the designer such decisions often appear in concrete form for all to see and few critics are likely to excuse mistakes or failures on the grounds of insufficient information. Designers, unlike scientists, do not seem to have the right to be wrong. While we accept that a disproved theory may have helped science to advance we rarely acknowledge the similar contribution made by mistaken designs.

An introduction to design as reflective practice

Kees Dorst

In 1983 Donald Schon reopened the discussion about the fundamentals of design and design methodology when he published 'The Reflective Practitioner'. In this sociological study of the behaviour of 'professionals', Schon included what he calls a 'primer' for a new theory of design. It is an alternative approach to design methodology at a very fundamental level.

1 • The theory of design as reflective practice

Schon's starting point is his feeling that the paradigm of technical rationality hampers the training of practitioners in the professions. He believes that the design-component of the professions is underestimated, and that the nature of human design activities is misunderstood. He shows that in the training programmes of professional schools that recognise design as a core activity, design knowledge is defined in terms of generalities about design processes and declarative knowledge needed to solve design problems. No attention is paid to the structure of design tasks and the crucial problem of linking process and task in a concrete design situation.

To Schon every design task is unique, a 'universe of one'. Therefore, one of the basic problems for designers is to determine how such a single unique task should be approached. This problem has always been relegated to the 'professional knowledge' of experienced designers, and was not considered describable or generalisable in any meaningful way. However, this does not satisfy Schon; he calls this tackling of unique design tasks the essence, the artistry of design practice. He finds fault with the prevalent analytical framework for failing to describe these activities, and regrets that their solving therefore cannot be taught in the professional schools. To describe the undertaking of fundamentally unique tasks, Schon proposes an alternative view of design practice, based on the idea that 'a kind of knowing is inherent in intelligent action' [Schon, 1983, p. 50]. This 'action-oriented', often implicit knowledge cannot be described within the paradigm of technical rationality. But Schon insists that this kind of knowledge is vital for action-oriented professions like design. He does recognise, however, that this implicit 'knowing-in-action' is difficult to describe and convey to students. What can be thought about and taught is the explicit reflection that guides the development of one's knowing-in-action habits. This he calls *reflection-in-action*.

Schon's theory is based on a constructionist view of human perception and thought processes. Through the execution of 'move-testing

experiments'(involving action and reflection), a designer is actively constructing a view of the world on the basis of his/her experiences.
In this paradigm, the basic elements of design activities are actions, and the kernel of the design ability is to make intelligent decisions about those actions. The results of these experimental actions are scrutinised by the designer, who reacts to this new state of his/her own making. The final design is a result of this interaction. In this 'reflective conversation with the situation', designers work by *naming* the relevant factors in the situation, *framing* a problem in a certain way, making *moves* toward a solution and *evaluating* those moves.
The frames are based on an underlying background theory, which corresponds with the designer's view about design problems and his/her personal goals. This background theory is not subject to change within design projects. But it can change over time, slowly and in tune with the professional and personal development of the designer.

Schon contrasts this theory with the positivistic rational problem solving approach:

> '...The positivist epistemology of practice rests on three dichotomies. Given the *separation of means from ends*, instrumental problem solving can be seen as a technical procedure to be measured by its effectiveness in achieving a pre-established objective. Given the *separation of research from practice*, rigorous practice can be seen as an application to instrumental problems of research-based theories and techniques whose objectivity and generality derive from the method of controlled experiment. Given the *separation of knowing from doing*, action is only an implementation and a test of technical decisions.
> In (the designer's) reflective conversation, these dichotomies do not hold. For him, practice is research like. Means and ends are framed interdependently in the problem setting. And his inquiry is a transaction with the situation in which knowing and doing are inseparable...'[Schon, 1987, p.78]

In this quote, Schon criticises the paradigm of technical rationality for introducing analytical dichotomies that, in his view, do not have any counterparts in practice.
As an alternative he proposes the categorisation of names, frames and moves. If this works, Schon may have made some real progress: to make a description of design activities that corresponds closely to design activities as they are experienced by its practitioners. In 'The Reflective Practitioner' and its sequel, 'Educating the Reflective Practitioner' [Schon,1987], the theory is illustrated by a thinking aloud protocol of an architectural design process. The well-written description of this protocol sparks immediate, intuitive recognition by designers. It could be one of the most accurate descriptions in design literature of some of the main problems facing designers. The description is definitely is much closer to the phenomenon of design than (most of) the more formal design methodology produced within the paradigm of technical rationality.

Avoiding the positivistic dichotomies of technical rationality might bring design methodology closer to design practice, but there is a price to pay. Not imposing these dichotomies makes it much harder to analyse design activities, since we must then consider a complex mixture of analysis, design and planning-oriented actions (mental and physical) as the subject of study. Classic divisions in design methodology, like that between 'design problem' and 'design solution' cannot be maintained within this paradigm. It may be true to life, but it is very difficult to handle and to wrench methods from that really help designers.

2 • The mechanism of reflection-in-action

Schon's theory does not include any sweeping statements about complete design processes or episodes, but presents a 'mechanism of design', which describes design activities at a much more detailed level. As such, it is comparable to the 'basic design cycle' of analysis-synthesis-simulation-evaluation that lies at the heart of the technical-rationalist approach (see the yellow book by Norbert [Roozenburg,1994]).

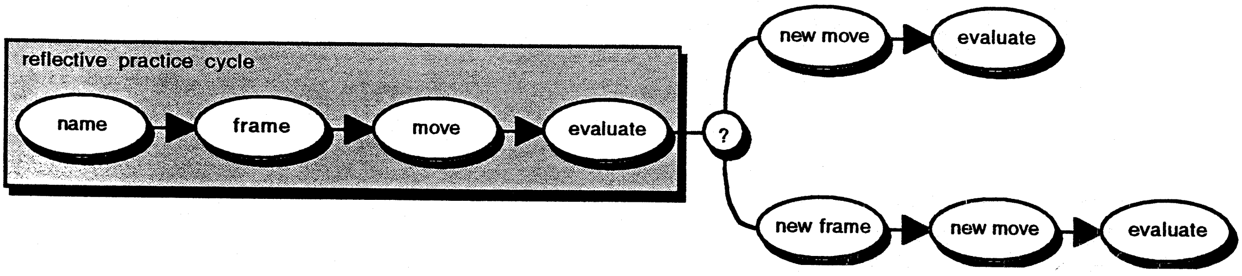

Figure 1 The basic cycle of reflective practice.

Reflection-in-action is a process of *naming, framing,* making *moves* and *evaluating* them (see Figure 1).
In the *naming* step the objects to be considered in the design situation are selected and named. In the *framing* step these named entities are put into a context, and an overall perspective on the design task is constructed. In making a *move* the designer takes an experimental action based on the naming and framing of the design task, and this action is then *evaluated.* The evaluation leads to either satisfaction, the making of new moves, or the reframing of the problem. The evaluation could also lead to a complete reconsidering of the designer's view of the design task, causing the designer to start *naming* new entities in the design situation.
There are three general criteria that are used in the move-evaluation step:

- Coherence: is this move well-directed in the light of the goal of the design activity, and is it consistent with earlier moves?
- Accordance with the performance specification: is this move within the bounds of an acceptable solution to the problem?
- The problem-solving value: has this move succeeded in reducing the problems, or has it led to more serious problems?

A complete design project consists of many of these reflective practice loops.

When we compare the reflective practice mechanism with its positivist counterpart, which is the basic design cycle (Figure 2), we see that all the design activities in the basic design cycle are also present in the mechanism of reflective design, but that they are grouped differently.

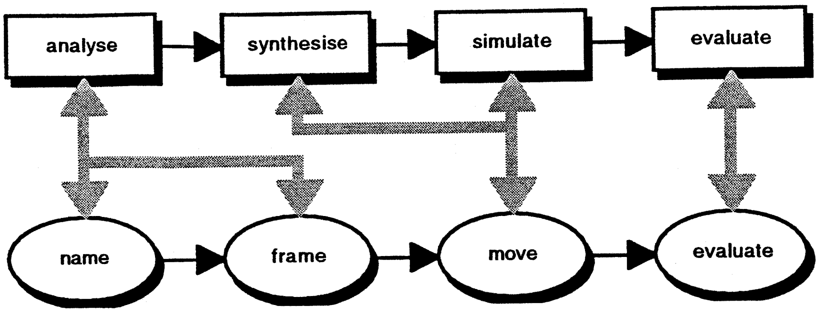

Figure 2 The correspondence between the elements of the basic design cycle (above) and the mechanism of reflective practice (below).

The *naming* and *framing* steps correspond mainly to the analysis step in the basic design cycle, though they also involve the construction of starting points for the synthesis-step. 'Making a *move*' is a combination of synthesis and simulation. The *evaluation* steps that are part of both mechanisms differ in character: in the basic design cycle, the design concept is evaluated on criteria derived from the problem statement and the performance specification, while in reflective practice, the design action, *move,* is judged on its effectiveness.

Schon used the metaphor of a 'reflective conversation with the situation' to describe the whole design process which results when using the mechanism of reflection-in-action. When making a move, the designer *speaks to the design situation,* observes and evaluates the results of his/her actions (the *back talk of the situation*). This conversational metaphor was introduced by Schon because it captures both the interactive nature of the reflective design mechanism and the 'satisficing' (or: negotiating) nature of design activities. A designer tries moves and observes the results knowing that not everything is possible, and that the completed design will be a 'negotiated settlement' between the designer and the design situation.

3 • An overview of the model

The paradigm of design as reflective practice is summarised in Figure 3. The categories and statements of the figure will now be treated in detail.

• The designer

The paradigm of design as reflective practice is founded on the more general paradigm of constructionism (see [Schon, 1987]). In constructionist epistemology, perception is a process of actively constructing a view of the world. An objective reality exists, but that reality only influences the world of the subject to a limited extent. The subject's perception of the world, his/her goals in constructing this personal world and the situation in which this 'imbuing with meaning' takes place are important influences on the world under construction. Human behaviour cannot validly be described or understood without including this constructed world-view.

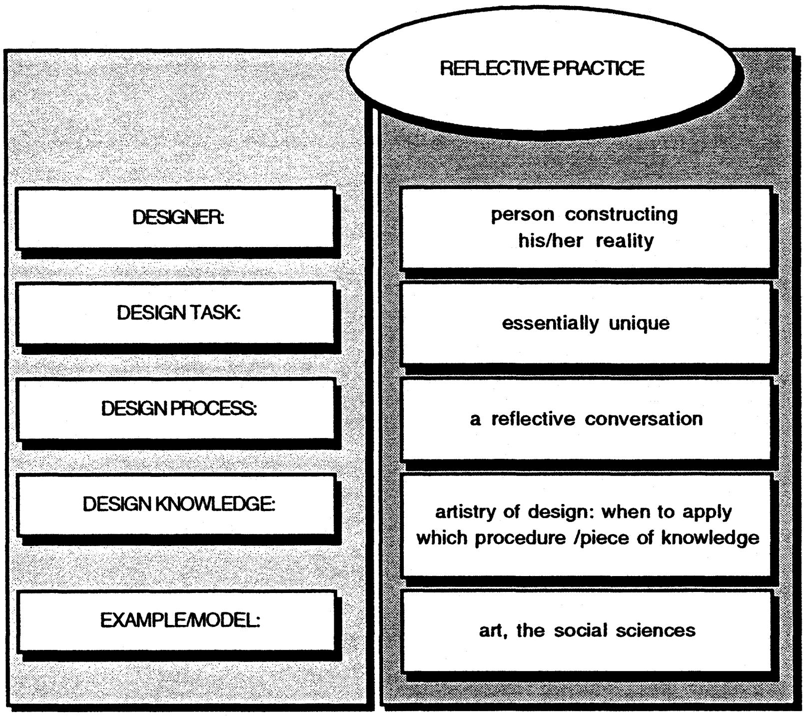

Figure 3 An overview of the paradigm of reflective practice.

• Design tasks

One of the basic assumptions of the theory of technical rationality is that there is a definable design problem to start with. Schon remarks that

> '.... Although Simon proposes to fill the gap between natural sciences and design practice with a science of design, his science can only be applied to well-formed problems already extracted from situations of practice...'

Schon, on the other hand, does not make any assumptions about the design problem, ill-defined or not. The description of design as a reflective conversation concentrates on the structuring role of the designer, setting the problem and outlining possible solutions all in one framing action. The strength of this framing action determines the amount of structure in the problem. In reflective practice design problems may be analysed and subdivided in a number of different ways, and there is no *a priori* way to determine which approach will be the more fruitful. Therefore, design problem and solution are always and inherently developed together.

• Design process

Designers do behave rationally, but will impose a network of names onto the design task and the design situation, and then frame the design task and solution. The designer's perception of the design task and the design situation exerts an important influence on this process.

The metaphor of the 'reflective conversation' describes a design activity as being controlled locally: people make moves and evaluate these on (among other things) the immediate problem solving value. The theory of reflective practice does not deal with higher level strategies, (comparable to the phases of rational problems solving), although it could easily be extended to contain them. A strategy could be seen as a (multiple) move, to be framed and evaluated like the single moves.

The essence of Schon's refection-in-action mechanism is that designers are active in structuring the design task, and that they do not evaluate concepts, but that they evaluate their own actions in structuring and solving the design task. The unit of 'doing design' that is manipulated and evaluated by the designer is not a 'topic' or a 'concept' (the static descriptive terms used in rational problem solving), but is dynamic: an action, a *move*.

• Design knowledge

According to Schon, general 'scientific' knowledge about strategies and methods for design has very limited use in design practice. The 'essence' or 'artistry' of design lies in the decision of *when to do what,* which strategies and methods to apply in which situation. Every design situation is essentially unique, and requires such structuring decisions by the designer.

• Example/Model

The philosophical basis of Schon's theories, constructionism and (indirectly) phenomenology, are closely related to some branches of the humanities. Design is seen as an artistic and deeply human process, the understanding of which requires the conceptual framework and an approach to research that has been developed for the study of human activities.

4 • Influence of the reflective practice paradigm

This is the way in which Schon strives to capture, describe and explain the essence of reflection-in-action in a reasonably rigorous and generalisable framework.

The rational problem solving paradigm has always had its doubters, reformers and heretics, but their discontent never reached a crisis point, and their views never spawned a complete alternative. Schon's theory is widely known throughout the design research community, it has not been widely accepted and used. There is broad consensus that the theory is interesting since it is fundamentally different from the rational problem solving approach, but that there is also a broad consensus that it is difficult to put to practical use. Recently, attempts have been made to extend Schon's primer into a design theory, to apply it, and to address some of its limitations (by Schon [1988,1992,1994] and others like [Bucciarelli, 1987]. Here at the faculty, Schon's theories are developed further by Rianne Valkenburg [Valkenburg, 1997].

KD, juni 1997

GENERIC DESIGN PROCESS IN ARCHITECTURE AND ENGINEERING: A DIALOGUE CONCERNING AT LEAST TWO DESIGN WORLDS

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Abstract.

The unconventional form of this paper is motivated by the authors' perceptions of important differences in architecture and engineering design and reflects differences, as well, in their approaches to the study of design process. One does participant/ observation studies of engineers at work; the other, protocol analyses of architects challenged with a specific design program. Both conclude that design is a complex social and dynamic process, not free of ambiguity and uncertainty. But there remain differences. Rather than force a reconciliation, they present in dialogue form their understanding of how designers design. This allows them not only more freedom in describing their individual theories, but also, with the inclusion of a third voice, the opportunity to entertain and answer criticism.

1 The Participants.

LLB: In order to better understand the engineering design process, I go into the firm much as an ethnographer might enter a remote village to study an aboriginal culture. I not only observe but also participate as an engineer in the day-to-day work of design and in this way my study differs from that of the anthropologist far from home. I join the world of participants in design, a world that at first strikes me chaotic, but then with time, settles into a more comfortable but still complex process.

DS: Your method interests me for I too work to understand the world of designers, architects in particular. I, too, see complexities that are hardly suggested in familiar models of designing. My methods call for carefully observing and recording what designers do and say -- their step-by-step drawing and information-seeking, their "loud thinking," their talk with other participants in the process -- in order to ground my attempts to describe and model design phenomena. I am an educated “fan” of designing, and I start from the assumption that good designers practice an art that they are only partly able to describe in words. My aim is to describe faithfully and, if possible, demystify the art of designing -- without reducing it to mechanical operations, or explaining it away.

Third Party: I welcome both of you to the world of design. For many years, I have taught design to students of engineering. I see it as the crowning subject in their professional education and sense that it is critical, as well, in the training of architects. To teach design is to attempt to teach the creative synthesis of solutions to problems. While so much of the engineering curriculum is narrowly aimed at developing analytical tools, we in design have a broader scope, a grander vision. Not that technical skills are unimportant; rather design calls for more heroic stuff. It is hard to teach, but we all recognize an innovative design when we see one, and some of us are dedicated to teaching students how to develop their creative and innovative skills.

2 What's a good theory of designing?

DS: How do designers design, indeed how do *good* designers design? That is what we hope to understand more fully. Now a good theory of designing would account for the main features that distinguish designing, from other kinds of purposeful, human activities -- for example, decision-making, problem-solving, modelling or analysis. It would also help to characterize design processes that are more likely to result in well-designed artefacts. Such theory would be useful to design instructors and their students, and useful for the development of design tools.

We believe that a good theory of designing must be general enough to include what practised designers do in such diverse fields as architecture and engineering. Although these two fields involve very different bodies of knowledge, skill and practice, they contain variants of an underlying generic process.

Third: A laudable aim, but be careful! There are really two parts to the design process: generating design proposals, and subjecting them to rigorous analysis; proposing and disposing. The second lends itself to theory-building and analysis, and it can be taught in the usual sense of "teaching." You can teach engineers the bodies of information, the models and techniques of analysis they need for purposes of evaluation. But the creative synthesis of solutions is not theorizable or teachable in the usual sense. Talented students can "get it" once they know enough about the special fields in which they work. They may pick it up on their own, or absorb it from their contact with a good, practised, designer. Teachers may give them useful hints, and examples to think about and imitate. But there are no rules or theories for creativity.

DS: I have a different view. It's a mistake to divide the process of design into creative and analytic components. For one thing, analysis itself is a creative activity: designers need to think up the criteria and methods by which to judge their images of design solutions.

Secondly, a good design process doesn't usually take the form of trial and error: evaluation of a proposal contributes to the generation of a new proposals. As a designer works his way through many proposals and evaluations, he learns about the distinctive properties of his design situation: it is this underlying learning process that needs to be understood, described and modelled.

Third: Maybe he learns. Still, all you ever see, at any stage of the process, are proposals and evaluations -- and the facts, techniques, and models used for evaluation.

3 Design Worlds and Objects Wolds

DS: If that's all you see, it's because you don't notice the stage on which the action is taking place -- the background on which proposals and evaluations depend. From the very first moment of a design process, the designer deals with a situation. If he's an architect, he's given a site and a program. There's a place where something is to be built, and there are the stakeholders (users, clients, neighbours, regulators) with their needs, wishes and preferences for the thing to be built. There are materials that may be used, methods of construction that may be employed, costs to be considered. Some features of site and program may come to the designer already described; much remains unsaid.

From the very beginning, the designer perceives, appreciates and describes the situation. he makes initial sense of it. He notices some things and ignores others. For example, he sees how the site lies in relation to a road; he observes a nice clump of trees. He notes the grades of slopes on the site, considers the possible orientation of a building, takes account of the angles at which summer and winter sun might fall on the buildings, the kind of neighbourhood in which the site is located. and he brings with him a repertoire of ideas, images, precedents, values, expectations and types -- some, particular to his identity as an architect; others, particular to the culture of which he is a member. Through this interaction between what he perceives and appreciates *in* the situation, he establishes an initial *coherence*. In effect, he constructs a world in which to design, a world of his own making; and it is this world that he captures, more or less fully and accurately, in his initial descriptions of the situation. When the architect is a practised designer, it is often astonishing how quickly he zones in on such a world and its description.

LLB: I believe much the same happens when the engineer engages in design, though I think he brings more of a design world with him to the task. I call this world an "object-world"; it is the world within which the designer, as you say, "perceives, appreciates and describes" the design task. The engineer, whether mechanical, electrical, or what have you, brings to the new design task a world whose elements, whose ingredients, what I think of as “furniture”, reflect his discipline and consist of concepts, images, rules of thumb, methods of analysis, functional relations, as well as tacit knowledge about hardware, objects, and artefacts. He has constructed this world, in part, through disciplined schooling and in part through experience designing - designing particular things like printed-circuit boards, shell structures, heat exchangers, CPM charts. Working within an object-world (and note that different participants in design will inhabit different object-worlds) he frames the "problem," by fitting it to the context he knows so well.

Third: I don't understand why you feel compelled to introduce this term "object-world" -- its too philosophical for my tastes. If you are claiming that engineers design objects when they design, why not just say so? Indeed, need it be said at all?

LLB: My focus is not on the objects they design -- that we indeed all understand is the case, although some of the "objects" engineers design can have a soft, almost immaterial existence. For example, I consider a Critical Path Chart or a control algorithm in software to be objects of design. Rather my focus is on the way engineers think and act when they design. I claim that their way is distinct from the ways designers deal with more conventional matters and distinct too from the modes of thought engaged by other professionals at work. This "way," unique to designers in engineering, I chose to label a world, and because this world of thinking and acting is a world of thinking and acting about objects, I call it an "object-world."
Think then of a world of mind and hand within which the participant in design "lives" while designing, while at the board, on the computer, or in intense conversation with a colleague while trouble shooting a prototype. Consider this world, if you like, as an environment, as a system of beliefs rooted in the objective world of engineering artefacts, a system of norms. which govern how objects themselves are perceived, how phenomena are understood and explained, and which define what qualities in a design are prized, what qualities discounted.

Third: If this way of thinking, of perceiving, of understanding, of creative thought is so unique, what are its special features?

LLB: First, in engineering we rely heavily upon abstraction and the quite severe reduction of phenomena to a minimum number of elements. These elements, whether an internal force in a mechanical structure, an inductive, capacitive, or resistive device in an electrical network, the actions denoted by the symbols or, a CPM chart, are all tailored to quantification.

Second, all of the ingredients of object-worlds function deterministically. "Explanation" means being able to give cause and effect type stories of phenomena -- why and how electrons flow, structures deflect under load, how a critical event might hold up a well-planned process.

Third, in our explaining, we rely upon a hierarchy of concepts and principles. Object-worlds are well structured. Indeed, my labelling these characteristics "first," "second," etc., is an example, albeit trivial, of object-world thinking in action.

Fourth, object-worlds are closed, finite worlds where conservation reigns supreme. Not just momentum and energy, but budgets have prescribed bounds. "There is no such thing as a free lunch" and "Life is a zero sum game" are commonly voiced tenets of this particular world.

Fifth, object-worlds are Cartesian in the sense that within them objects fill up space and no two can be in the same place at the same time. Simplicity and clarity are prized, ambiguity not tolerated. A final design drawing must make clear how objects fill space and are related to one another in a unique way. Visual ambiguity is error --often the subject of a visual joke seen posted on the walls above the designer's desk.

Sixth, time has a dual quality: It is both a resource to be distributed, conserved, used up, and, at other times, a background dimension, a quantity continuously flowing against which one measures sequences of events.

I make no claim that these are a unique or even a full ensemble of characteristics of the way participants in engineering design think and act while designing but I do believe that they are useful, particularly in understanding what others may take as commonplace but what I see as critical features of the design process.

For example, design participants' beliefs in hierarchy and conservation frame their construction of “trade-offs” -- well constructed situations where a choice must be made among options. This balancing act is seen as a measured act too and an “optimum” or at least a satisfactory solution, subject to the (fixed) constraints on the problem, is thought to be attainable. Now, in my mind, this notion of trade-off is not sacred but an artefact of object-world thinking. It is not inherent in the design problem but a construction of participants in design. If you accept this possibility then new ways of understanding the design process open up to view.

DS: It looks to me that what you are calling "object world" is what I have referred to as "repertoire of ideas, images, precedents, values expectations and types."

LLB: Yes, that fits well with my intended meaning.

DS: And just as you can explore the controlling dimensions of the engineer's object world, so too I can ask for the architect: What sorts of things are in an accomplished designer's repertoire? How are they deployed to help the designer make sense of new design situation? Where do they come from?

Third: That strikes me as a useful question.

DS: We can recognise two kinds of sources. There are vernacular types that "grow up" in a society as a traditional way of building -- a Mediterranean fishing village, a 17th century Amsterdam town house, Amish farm communities, African villages, and closer to home, New England farm houses, so mundane and ordinary we may fail to see them as type.

A second source lies in the work of individual architects who through their own efforts create a type; e.g., Mies Van der Rohe's glass towers, Frank Lloyd Wright's Usonian houses. Now it seems to me that the existence of individually generated types makes it clear that types are also the basis of design worlds. And while my Design World is more of a construct produced in response to the immediate design program presented to the architect and while its norms and "furniture," as you put it, might be quite different in many respects, the notion that the designer in both cases thinks and acts, figures and sketches, working within such a cognitive domain is common to both our descriptions.

LLB: There are other resonances. In engineering design we have our own vernacular types in the traditions of the artisan, the mechanic, the millwright, the craftsman. They too had their object worlds. But today indoctrination into the world of technique is more a matter of formal higher education as well as experience on the job.

DS: Accepting these notions of design world and of object world we must ask, how does the designer move within them? I propose that designing can be understood as a sequence of transformations. At the level of description, it can be understood as a sequence of descriptions that converge on specifications for a building to be built. But the prior question to be asked in constructing a theory of designing is how such coherent design worlds are established in the first place? How do processes of perception, appreciation and description combine to enable practised designers to frame a manageable, coherent design problem to be solved?

Once you pose the question in this way you see that the designer's further moves, and his evaluation of their consequences and implications, are ways of testing out and transforming an initial framing of the situation. Proposals and evaluations of proposals *within* a constructed design world are ways of learning about and transforming essential features of that world.

Third: Isn't all this is a just a long-winded way of saying that, as a design process proceeds, the designer adds or subtracts or modifies the requirements against which he will evaluate his proposals? The process is still fundamentally divisible into a set of requirements, or constraints, and proposals to be tested against those requirements.

DS: But this comes from focusing your attention on a slice of the process. How do requirements get in there in the first place? And how do they come to take the form of a *coherent* set of requirements that set the directions in which the designer makes and tests his further moves? And how do we account for the well-recognised fact that different, equally skilful designers, faced with what looks to an outsider like "the same situation," construct different design worlds and frame different design problems or establish different requirements?

4 Models of Designing in Engineering.

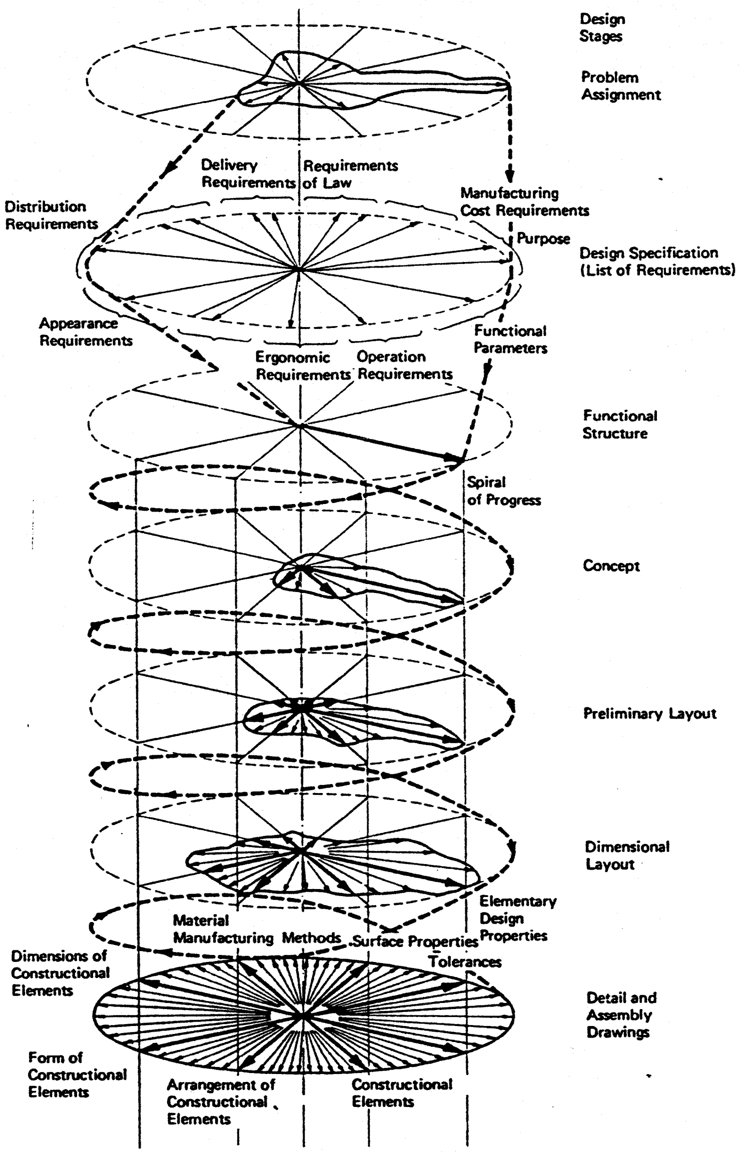
Third: Well, perhaps what you say is true of architecture. But if so, it is because architecture lacks a discipline -- and therefore, no rigorous, uniform theory of architectural designing is possible. I am often mystified by the explanation an architect will give for why his design is as it is. It seems to be that different, equally skilful designers design differently, given the same situation, because of the artistic freedom they have, a freedom reflected in the language they employ. Your characterisation of designing is certainly not true of engineering design, and I doubt that it holds for those aspects of architectural designing that are more like engineering.

LLB: It does seem that in engineering design we talk in a "harder" technical dialect, our rational explanations suggest an accomplished design, if not optimum and unique, is at least one of the better or "satisficing," in the words of Simon. This kind of rational justification for why the design is as it is, in turn, leads many to view the design process itself is a disciplined exercise, capable of being understood in the same disciplined way.

Third: That indeed is the case: In engineering design we can develop quite sophisticated models of the design process. The figure shows an example taken from Hubka. "... Each design stage requires a period of *time* to be performed, and results in progressive increase in available information,... It is useful to divide the considerations into smaller stages: (1) A full *design specification* is drawn up, as independent as possible of any hardware solution, including implications from the socio-technical sphere, and evaluation criteria. (2) Search for alternative *processes*, and conceptual structures that describe functions to be performed (again as independent as possible from hardware solutions!. An evaluation process at this state of the work should eliminate those functional structures that are obviously inadequate. (3) Investigate alternative function-carriers, i.e. general types of functional surface arrangements (organs) that could perform the functions, and exert the necessary effects on the process. A second evaluation takes place now. Development of *preliminary lay-outs*, usually in sketch form, to deliver the skeletons of hardware solutions with only the main function-carriers more closely defined. This is again followed by an evaluation. (5) The selected preliminary lay-out is turned into a *dimensional lay-out* true to scale, from which (6) Detail drawings are produced in the final design stage." [Eder, "Models of Engineering Design in Education" 19B3 ASEE Annual Conference Proceedings].

LLB: This is a fine example of the normative model I have in mind, of the kind showing object-world thinking in action. Note how time flows from top to bottom as the process advances through its various stages, each stage consuming a definite amount of time. One stage determines and is prerequisite to the next. Note, too, how the dotted circle implies that there is a finite, bounded amount of design to be done, and how that effort can be further reduced to sub-tasks. The circle is filled up when the design process nears completion. You can see how in retrospect, again working within this world, one might construct the casual links, fabricate the story of the design's evolution. Note too how your description is all in the passive voice -- all design thinking, sketching, feed backing, acting, testing happens somehow, but who is responsible, whether an individual, a team, a firm, the reader has no clue.
But it's not just the way you describe the design process that interests me, rather I claim that the figure and your account of process, what you construe as a model is seriously deficient. It is not a good basis for an explanatory theory, for when compared with the design process as I have observed it, these visions fail to capture what I claim are essential aspects of the design process.

Third: Are you claiming that design is not organised this way? If so, I think you are in error. Certainly from what I have seen in industry it is clear that design proceeds through stages as shown in the figure. Now I admit that details may differ, but this is meant to be a generic model of process.



Hubka, V., Principles of Engineering Design, Butterworth, 1982, p. 35

5 Design as a Social Process.

LLB: I don't deny that design proceeds in time through stages or that design is organised in this way. (The latter doesn't necessarily mean that the model is good theory). What I object to is how this generic model, and others like it, imply that there is one single omniscient agent carrying out all of the design tasks at each and every stage -- an agent that could be imagined as an individual entrepreneur, as a design team, or as an engineering firm. But whoever or whatever is doing the design, evidently does so as a coherent, single minded actor. Now in my studies of design, on site, I see many different individuals participating in the design task, working at all of the various stages shown in your model. Each participant, while given responsibility for a different aspect of design, still must work together with all other participants if good design is to happen. What I observe is that this is not so coherent a process as the model implies.

DS: You urge that we add a new dimension to our study of design -- that design is not the province of a single mind, a single world... we need another metaphor....perhaps that of a "market place."

LLB: I prefer "process-world." Yes, for the model before us fails to suggest the diversity of perspectives, diversity of object worlds, that "collide" in engineering design.

Third: You must be referring again to “trade-offs”; how when apparently conflicting constraints or design requirements are resolved though creative exploration of options, analysis of different possibilities, comparing their relative worth. "Object worlds in collision" is a bit too dramatic for my tastes, after all, trade-offs generally produce a satisfactory melding of what, at the start, may appear to be conflicting requirements.

LLB: Excuse my rhetoric but my intent is to locate what is going on within a social process, a process, a world within which it is the different perspectives of participants that get resolved. By describing trade-offs solely in terms of object-world apparatus (constraints, performance specifications) you miss what truly happens in the design process. It's not just a matter of doing the best one can, given a set of constraints, but also a matter of the latter's reconstruction, distortion, and elaboration or even dismissal in the minds of the participants.

Third: But what is the difference? I talk about trade-offs in terms of technical constraints. You talk about trade-offs in terms of participants' opinions about the relative importance of the constraints. We both end up at the same place, don't we?
LLB: You presume that different participants have the same full understanding of the choice to be made, that each and every one sees and understands each constraint the same way, though they value them differently. I suggest that participants from different worlds "see" the "problem" and its constraints differently. There is no omniscient vision shared by all participants of what it is they are up to.
You yourself would readily admit that anything but the simplest design task is broken up into a set of different, preferably independent tasks, and that different participants with different expertise are given the responsibility to work out their own subsytem or component designs subject to constraints that ensure their work will mate with others.

Unfortunately, (1) these "interface constraints" can never be specified a priori to the level of detail that would enable designers to work independently of one another -- there is to much uncertainty inherent in the process; and (2) it is impossible to draw a clean boundary or envelope around one subsystem, distancing it from another to insure independence of effort even when uncertainty is relatively minimal. Functional relationships are intertwined no matter how “clean” and abstract any one of the onjectworld disciplines engaged might appear.

Now these different participants -- and allow me to include all members of the design team, including individuals responsible for manufacturing, for reliability, even for marketing -- will see the interfaces differently, will see the design task in-the-large somewhat differently, will not describe the forms and functions of the intended artifact in the same language. In this process, whenn concepts are generated and massaged, when sketches are sketchy, lines and numbers symbolic and suggestive rather than precisely instrumental, in short before the design is an accomplished reality some meanings are bound to be ambiguous.

DS: You bring to my mind a vision of design as a dialogue, an inquiring dialogue among individuals who play different roles within an institutional context. I see much the same thing in architecture. Think of the interaction of an architect, a contractor, a structural engineer and a user in the design of a building. Each brings to their roles different bodies of language, knowledge and interests.

LLB: These are the ingredients of what I have called the engineer's "object-world."

DS: And the language is very important in this dialogue: An architect, contractor, structural engineer, a user of the building -- each operates within a world, a design world of their own with its own language, its own rules, for understanding the design. For an architect, the design is composed of formal elements and functions (edge, boundary, zone, for example) and the rules are expressible in such terms as "implication," "consistency," "stability," "intensity," and the like. For a building contractor, the design is a system of building processes, and its rules are related to efficiency of construction, maintenance or management, operations on materials, ease of handling, times to complete, and the like. For the structural engineer, the design is a building understood as a frame structure subject to physical forces, a structure described in terms of its stability, load-carrying capacity, factors of safety. In each instance the rules and constraints guiding each participant’s thought about the design may be more or less explicit in the language they use to describe their work. It is in all cases implicit in their decisions.

Disagreement among participants tend to be couched in terms of descriptions of the qualities and functions of the various worlds of the participants; for example,

> Architect: "I want a wall here separating this interior zone from the terraces there. It must be freestanding, set off from the inner wall and screen, cut to make the interior meeting room visible from the outside, but protected."
>
> Contractor: "You're asking me to build two walls where one would do. I'll have to sequence three trades in there. It will take twice as long to build and cost three times as much."

Some terms may appear in the lanauages of all the participants -- for example, "wall," "room," "window," "opening" -- but they carry different, though overlapping meanings. "Wall" is an element that demarcates the edge of a zone, shows a certain texture; it is composed of bricks, costs so much to build; it bears such and such a vertical load. "Wall" refers to a cluster of qualities and objects. Its referents are not related to one another as are terms within a single design world laguage.
These several languages of participants in a design process, along with their rules and tacit models, can be seen as the loci of appreciative systems of design qualities. Designers move within these worlds but their moves have consequences and implications accross worlds.

LLB: This is what I was referring to whenn speaking of how the work of an engineer on one side of an interface will always have implications for others working elsewhere, on other subsystems. In this setting, disagreements often arise, and often under conditions of uncertainty and ambiguity; and individuals inquire and negotiate with one another, employing different lanauages and images of the relevant field of constraints in order to arrive at consensus about the thing to be designed.

DS: Much the same goes on in architecture although the architect appears to claim more authority in defining and arbitrating design characteristics. An architect ought to be -- and sometimes is -- enough of a builder, engineer and user to pick up and make sense of others' language and meanings and incorporate them into his own work, his own design criteria and moves. He needs to be able to speak more than one design language (though not necessarily as a native speaker) and enter into the several worlds to which these languages refer. Design disagreements can arise in the work of the individual architect designing, as you have observed them in the interplay of participants on an engineering design team. In both contexts the resolution of disagreements does not take the form of "translation" of the several languages into a common language, but in a dialogue that consists of "talking across languages."

Third: Your argument for ambiguity would be compelling if words were all that designers used when communicating across different design worlds, as you would say. But words are cheap in design. What really counts is the formal specification of the artifact's characteristics. This ordinarily is done with a picture, a drawing, not words. Now there is nothing ambiguous about a professionally executed drawing.

LLB: What you say may be true of the formal detailed and assembly drawings that are produced in the final stages of a design but it is certainly not true of the kinds of pictures, images, diagrams, and sketches designers pen in all other stages. Here the rough sketch of a load path through a structure, drawn by one engineer to inform another can be just as fuzzy an image, just as object-world bound as any words describing the same.

DS: Similarly an architect's diagram can symbolically show the organization of space with little reference to the precise spatial dimensions of a site and, hence, be might be fully understood only within his design world. But why not consider the language of design to include the conventions of the sketch, the diagram?
Note that these too, as we have claimed, are often qualitative. In architecture, for example, designers make reference in sketching as well as in words to such qualities as "enclosure," "directionality," "privacy," "accessibility" and "permeability." Furthermore, when several different individuals participate in a design dialogue architect, engineer, contractor -- each one employs his own design language, each will take a turn at showing through a sketch what he or she means. Now, we claim that there is no common language nor common drawing convention, working at all levels in which the different dialects of participants in a design process are soluble. Hence the design disagreements, whatever else they may involve, pivot on incongruent descriptions; and participants deal with these according to norms defined by the particular cultural context they inhabit.

LLB: ...the particular process world they inhabit.

Third: I can not go alony with all of this obfuscation. Surely the statement of performance specifications at the outset, right at the very start of the design process, is hard and fast knowledge, written out clearly in usually a contractual kind of document. Doesn't that set of constraints define the donmain within which the creative designer must seek a solution?

DS: Certainly constraints exist at the outset of the design process and do so througout. What we challenge is the simple notion that these are (1) unambiguous and (2) sufficient to define the design problem so that designers can go about their creative efforts without another word or question. Still constraints exist. But they change, they grow in number, some vanish or are rephrased, all take on new meanings and are amplified as design progresses.

LLB: In short constraints are constructed elements of the design process. In a sense they to are "designed", and negotiated in the process.

DS: Perhaps you go to far. For designers do talk in terms of constraints at any point in the design process, constraints do in fact exist. And a "constraint model" of design proves to be a useful model for testing our notions about design process. Not only do designers recognize it as bearing some relation to an important dimension of their work, but it is a useful vehicle for testing an exploring the notion of design worlds, of design as a social process. The "negotiation" or "management" of constraints are popular phrases among some working in the field of computer-aided design.

LLB: I did not mean to suggest that constraints do not exist in design or that they are unimportant or infinitely malleable. Indeed, quite the contrary, I claim that whitout them, design would be impossible.

DS: Now you go overboard in another direction. What do you mean "impossible"?

LLB: I mean that constraints guide and promote design thought as much as restrict it. Without constraints, the designer is like a sea, a perfectly calm sea, in a circular hot tub, at the equator, on the day of the equinox, with the sun at its zenith, and not a bird or cloud in the sky. Which way should he paddle? How creative might this Robinson Crusoe be? I submit that, in this state of unconstrained, perfect rotational symmetry, there is no opportunity for creative thought. Only when the sun moves, a wind springs up from the south bearing a soaring bird, is creative design, planning possible. So too in professional design worlds, constraints configure our thoughts, suggest design moves as much as limit them.

DS: But note how these constraints in your example rely upon the "reading" given these signs by your heroic navigator. The full implications of a constraint are never fully explicit. Designers must fill in the meaning for themselves.

LLB: Yes, and in engineering design that filling-in is usually done in a dialogue among all participants, either in a formal or informal setting. Sometimes, when different participants are affected differently by different possible readings, this takes the form of a negotiation, even a barter or trade.

Third: All that you have said leaves me asea. I would like you to tell me the significance of your vision of design process -- in particular, as you made reference to computer-aided design -- show me that your vision matters.

DS: Fair enough, after all since you offered to pay for lunch we do owe you something. But first, allow me to summarize.
Design, focusing first on the individual designer designing, is an intense activity engaged within a design world, or within an object world. These worlds are cognitive domains that enable the designer to frame and understand the design task. They are personal to an extent but also culturally shared.
Design process, focusing now on all actors participating in the desiyn, is a social process conducted within definable subcultures, e.g., an engineering firm. Because different participants in design work within different worlds, they will see the design differently, and must engage in a continuing dialogue in order to produce a design. This process, not unlike a negotiation at times, is potentially rich with ambiguity and uncertainty.
Constraints run through the whole process from beginning to end. Constraints, though are not given a priori but must be fleshed out, filled in, fabricated, even trown away or simply forgotten in the process of dialogue and negotiation. Constraints, in a sense are to be designed.
Now let us turn to what this might mean for the development of computer aids to design.
Betreffende deel van het paper is weggelaten

DS: I think it's time we bring this dialogue to a close. Our purpose has been to explore a perspective on design in both architecture and engineering that sees design as a dynamic process, one in which the designer shapes and imagines, calculates and trades off within a design world which is personal though culturally shared. We see it also as a social process, an interactive process where constraints are negotiated, where ambiguity and uncertainty are present, and where consensus may be finally said to have been achieved only when the artifact is given its final physical form.
With this vision of design, a vision based upon the design process observed, rather than normative models of how it ought to be structured, certain consequences follow for the design of computer aids. Like any tool, they should be available for appropriation by the user.

Discovering Design Ability

Nigel Cross

Introduction

Perhaps the most significant development in the discipline of design studies has been the emergence and growth of respect for the inherent strengths of design ability. The infant discipline seemed, thirty years ago, to have been founded on a disrespect for natural design ability and with a strong desire to scientize design. The desire was to recast design in an image of science, and to replace conventional design activities with completely new ones.

These original aims may well have been an understandable reaction to a previous view of design as an ineffable art, and the deification of hero-figure designers. There are still those, outside the discipline of design studies, who regard design as ineffable, and there are still those, within but on the fringes of the discipline, whose lack of understanding of design ability still leads them into attempts to reformulate design activities in inappropriate ways. However, at the core of the discipline there is, I believe, a more mature and enlightened view of design ability.

This mature view has grown from a better understanding of the nature of design ability, from analysis of its strengths and weaknesses, and from a desire to defend and nurture that ability. In a previous paper[1] I called for a research program in design studies based around the "touchstone theory"[2] of the legitimacy of designerly ways of knowing, thinking, and doing. In this paper I wish to outline some of the "defensive theories" that have grown around this touchstone.

Dictionary definitions of design (as a verb) usually refer to the importance of "constructive forethought," or, as Gregory puts it, "Design generally implies the action of intentional intelligence."[3] I shall try to develop a more explicit view of this constructive, intentional intelligence.

1. Design Ability Has Distinctive Features

When designers are asked to discuss their abilities and to explain how they work, a few common themes emerge. One theme is the importance of creativity and intuition. For example, engineering designer Jack Howe has said: "I believe in intuition. I think that's the difference between a designer and an engineer. . . . I make a distinction between engineers and engineering designers. . . . An engineering designer is just as creative as any other sort of designer."[4] Some rather similar comments have been made by industrial designer Richard Stevens: "A lot of engineering design is intuitive, based on subjective thinking. But an engineer is unhappy doing this. An engineer wants to test; test and measure. He's been brought up this way and he's unhappy if he can't prove something. Whereas an industrial designer, with his Art School training, is entirely happy making judgements which are intuitive."[5]

Another theme that emerges from designers' own comments is based on the recognition that problems and solutions in design are closely interwoven—that "the solution" is not always a straightforward answer to "the problem." For example, commenting on one of his more creative designs, furniture designer Geoffrey Harcourt said, "As a matter of fact, the solution that I cam up with wasn't a solution to the problem at all. I never saw it as that. . . . But when the chair was actually put together [it] in a way quite well solved the problem, but from a completely different angle, a completely different point of view."[6]

A third common theme is the need to use sketches, drawings, and models of all kinds as a way of exploring problem and solution together, and of making some progress when faced with the complexity of design. For example, Jack Howe has said that, when uncertain how to proceed: "I draw something. Even if it's 'potty' I draw it. The act of drawing seems to clarify my thoughts."[7] Given the complex nature of design activity, therefore, it hardly seems surprising that structural engineering designer Ted Happold should suggest that "I really have, perhaps, one real talent; that is that I don't mind at all living in the area of total uncertainty."[8] If that seems a little too modest, there are certainly other designers who seem to make more arrogant claims, such as architect Denys Lasdun: "Our job is to give the client, on time and on cost, not what he wants, but what he never dreamed he wanted; and when he gets it he recognises it as something he wanted all the time."[9] Despite the apparent arrogance, there is the truth in this statement that clients often do want designers to transcend the obvious and the mundane, and to produce proposals which are exciting and stimulating as well as merely practical.

From this brief review so far, we can summarize the major aspects of what designers do. Designers

- produce novel, unexpected solutions
- tolerate uncertainty, working with incomplete information
- apply imagination and constructive forethought to practical problems
- use drawings and other modeling media as means of problem solving

2. Design Ability Can Be Articulated

For thirty years now, there has been a slowly growing body of understanding about the ways designers work, based on a wide variety of studies of designing.[10] Some of these studies rely on the reports of designers themselves, such as those we have just seen, but there is also a broad spectrum of studies, running through observations of designers at work, to experimental studies based on protocol analysis, knowledge elicitation for expert systems, and theorizing about the nature of design ability.

Such studies often confirm the comments of designers themselves, but try also to add another layer of explanation of the nature of designing. For example, one feature of design activity that is frequently confirmed by such studies is the importance of the use of conjectured solutions by the designer. In his pioneering case studies of engineering design, Marples suggested that "the nature of the problem can only be found by examining it through proposed solutions, and it seems likely that its examination through one, and only one, proposal gives a very biased view. It seems probable that at least two radically different solutions need to be attempted in order to get, through comparisons of sub-problems, a clear picture of the 'real nature' of the problem."[11] This view emphasizes the role of the conjectured solution as a way of gaining understanding of the design problem, and the need, therefore, to generate a variety of solutions precisely as a means of problem analysis. It has been confirmed by Darke's interviews with architects, where she observed how they imposed a limited set of objectives or a specific solution concept as a "primary generator" for an initial solution: "The greatest variety reduction or narrowing down of the range of solutions occurs early on in the design process, with a conjecture or conceptualization of a possible solution. Further understanding of the problem is gained by testing this conjectured solution."[12] The freedom—and necessity—of the designer to redefine the problem through the means of solution-conjecture was also observed in protocol studies of architects by Akin, who commented: "One of the unique aspects of design behaviour is the constant generation of new task goals and redefinition of task constraints."[13]

It has been suggested that this feature of design behavior arises from the nature of design problems: they are not the sort of problems or puzzles that provide all the necessary and sufficient information for their solution. Some of the relevant information can be found only by generating and testing solutions; some information, or "missing ingredient," has to be provided by the designer himself, as suggested by Levin from his observations of urban designers: "The designer knows (consciously or unconsciously) that some ingredient must be added to the information that he already has in order to arrive at a unique solution. This knowledge is in itself not enough in design problems, of course. He has to look for the extra ingredient, and he uses his powers of conjecture and original thought to do so."[14] Levin suggested that this extra ingredient is often an "ordering principle," and hence we find the formal properties that are so often evident in designers' work, from towns designed as simple stars to teacups designed as regular cylinders.

Designers, however, do not always find it easy to generate a range of alternative solutions in order to better understand the problem. Their ordering principles or primary generators can, of course, be found to be inappropriate, but they often try to hang on to them because of the difficulties of going back and starting afresh. From his case studies of architectural design, Rowe observed: "A dominant influence is exerted by initial design ideas on subsequent problem-solving directions. . . . Even when severe problems are encountered, a considerable effort is made to make the initial idea work, rather than to stand back and adopt a fresh point of departure."[15] This tenacity is understandable but undesirable, given the necessity of using alternative solutions as a means of understanding the real nature of the problem. However, Waldron and Waldron, from their engineering design case study, came to a more optimistic view about the self-correcting nature of the design process: "The premises that were used in initial concept generation often proved, on subsequent investigation, to be wholly or partly fallacious. Nevertheless, they provided a necessary starting point. The process can be viewed as inherently self-correcting, since later work tends to clarify and correct earlier work."[16]

It becomes clear from these studies of designing that architects, engineers, and other designers adopt a problem-solving strategy based on generating and testing potential solutions. In an experiment based on a specific problem-solving task, Lawson compared the strategies of architects with those of scientists, and found a noticeable difference: "The scientists were [attempting to] discover the structure of the problem; the architects were proceeding by generating a sequence of high-scoring solutions until one proved acceptable. . . . [The scientists] operated what might be called a problem-focussing strategy. . . . In a supplementary experiment, Lawson found that these different strategies developed during the architects' and scientists' education; while the difference was clear between fifth-year, postgraduate students, it was not clear between first-year students. The architects had therefore learned their solution-focusing strategy, during their design education, as an appropriate response to the problems they were set. This is presumably because design problems are inherently ill-defined, and trying to define or comprehensively to understand the problem (the scientists' approach) is quite likely to be fruitless in terms of generating an appropriate solution within a limited timescale.

The difference between a scientific approach and a design approach has also been emphasized in theoretical studies, such as Simon's, who pointed out that "The natural sciences are concerned with how things are. . . . Design, on the other hand, is concerned with how things ought to be."[18] And March has categorized the differences between design, science, and logic: "Logic has interests in abstract forms. Science investigates extant forms. Design initiates novel forms. A scientific hypothesis is not the same thing as a design hypothesis. A logical proposition is not to be mistaken for a design proposal. A speculative design cannot be determined logically, because the mode of reasoning involved is essentially abductive."[19] This "abductive" reasoning is a concept from the philosopher Peirce, who distinguished it from the other more well-known modes of inductive and deductive reasoning. Peirce suggested that "deduction proves that something must be; induction shows that something actually is operative; abduction merely suggests that something may be."[20] It is therefore the logic of conjecture. March prefers to use the term "productive" reasoning. Others have used terms such as "appositional" reasoning in contradistinction to propositional reasoning.[21]

Although March, Simon, and others have attempted to construct various forms of "design science," they have been careful to distinguish this from popular conceptions of deductive scientific activity. Cross and Naughton have also pointed to the potential error of basing models of design activity on naive views of the epistemology of science,[22] and Glynn has suggested that scientists actually might have something to learn from the epistemology of design.[23]

Design ability is founded on the resolution of ill-defined problems by adopting a solution-focusing strategy and productive or appositional styles of thinking. However, the design approach is not necessarily limited to ill-defined problems. Thomas and Carroll conducted a number of experiments and protocol studies of designing and concluded that a fundamental aspect is the nature of the approach taken to problems, rather than the nature of the problems themselves: "Design is a type of problem solving in which the problem solver views the problem or acts as though there is some ill-definedness in the goals, initial conditions or allowable transformations."[24] There is also, of course, the reliance in design upon the media of sketching, drawing, and modeling as aids to the generation of solutions and to the very processes of thinking about the problem and its solution. The process involves what Schon has called "a reflective conversation with the situation." From his observations of the way design tutors work, Schon commented that, through sketches, the designer "shapes the situation, in accordance with his initial appreciation of it; the situation 'talks back,' and he responds to the back-talk."[25]

Design ability therefore relies fundamentally on nonverbal media of thought and communication. This deep-seated aspect of design ability perhaps accounts for designers' traditional reluctance, or inability, to verbalize their skill. Some commentators have even suggested that there may even be distinct limits to the amount of verbalizing that anyone can productively engage in about design ability. Daley has suggested that "the way designers work may be inexplicable, not for some romantic or mystical reason, but simply because these processes lie outside the bounds of verbal discourse: they are literally indescribable in linguistic terms."[26] This view throws into doubt my claim that design ability can indeed be articulated. I hope I have provided enough evidence to refute the nonverbalizers, and to show that empirical design studies have led to some coherent articulation of features of design ability.

This review of studies of designing enables us to summarize the core features of design ability as comprising the abilities to

- resolve ill-defined problems
- adopt solution-focusing strategies
- employ abductive/productive/appositional thinking
- use nonverbal, graphic/spatial modeling media

3. Design Ability Is Possessed by Everyone

Although professional designers might naturally be expected to have highly developed design abilities, it is also clear that nondesigners also possess at least some aspects, or lower levels of design ability. Everyone makes decisions about arrangements and combinations of clothes, furniture, and so forth—although in industrial societies it is rare for this to extend beyond making selections from available goods that have already been designed by someone else. In other societies, however, especially nonindustrial ones, there is often no clear distinction between professional and amateur design abilities—the role of the professional designer may not exist. In craft-based societies, for example, craftspeople make objects that are not only highly practical but often also very beautiful. They would therefore seem to possess high levels of design ability, although in such cases, the ability is collective rather than individual: the beautiful-functional objects have evolved by gradual development over a very long time, and the forms of the objects are rigidly adhered to from one generation to the next. Even in industrial societies, with a developed class of professional designers, there are often examples of vernacular design persisting, usually following implicit rules of how things should be done, similar to craftwork. Occasionally there are examples of "naive" design breaking out in industrial societies, with many of the positive attributes that naive art has. A classic example is the "Watts Towers"—an environmental fantasy created by Simon Rodia in his Los Angeles backyard between the nineteen-twenties and fifties.

Recently, in architecture especially, there have been moves to incorporate nonprofessionals into the design process, through design participation[27] or community architecture.[28] Although the experiments have not always been successful—in either process or product—there is at least a recognition that the professionals could, and should, collaborate with the nonprofessionals. Knowledge about design is certainly not exclusive to the professionals. A strong indication of how widespread design ability is comes from the introduction of design as a subject in schools. It is clear from the often very competent design work of schoolchildren of all ages that design ability is inherent in everyone.

4. Design Ability Can Be Damaged or Lost

Although some aspects of design ability can be seen to be widespread in the general population, it has also become clear that the cognitive functions upon which design ability depends can be damaged or lost. This has been learned from experiments and observations in the field of neuropsychology, particularly the work which has become known as "split-brain" studies.[29]

These studies have shown that the two hemispheres of the brain have preferences and specializations for different types of perceptions and knowledge. Normally, the large bundle of nerves (the corpus callosum) which connects the two hemispheres ensures rapid and comprehensive communication between them, so that it is impossible to study the workings of either hemisphere in isolation from its mate. However, in order to cure epilepsy, some people have had their corpus callosums surgically severed, and became subjects for some remarkable experiments to investigate the isolated functions of the two hemispheres.[30]

Studies of other people who had suffered damage to one or other hemisphere had already revealed some knowledge of the different specializations. In the main, these studies had shown the fundamental importance of the left hemisphere, which controlled speech functions and the verbal reasoning normally associated with logical thought. The right hemisphere appeared to have no such important functions. Indeed, the right became known as the "minor" hemisphere, and the left as the "major" hemisphere. Nevertheless, there is an equal sharing of control of the body; the left hemisphere controls the right side, and vice versa, for some perverse reason known only to the Grand Designer in the Sky.

This left-right crossover means that sensory reception on the left side of the body is communicated to the brain's right hemisphere, and vice versa. This even applies, in a more complex way, to visual reception; it is not simply that the left eye communicates with the right hemisphere, and vice versa, but that, for both eyes, reception from the left visual field is communicated to the right hemisphere, and vice versa. Ingenious experiments were therefore devised in which visual stimuli could be sent exclusively to either the left or right hemisphere of the split-brain subjects. These experiments showed that the separated hemispheres could receive, and therefore "know," separate items of information. The problem was how to get the hemispheres to communicate what they knew back to the experimenter. The left hemisphere, of course, can communicate verbally, but the right hemisphere is mute. Some experimenters resolved this problem by visually communicating a word or image to the right hemisphere, and asking it to identify a matching object by touch with the left hand.

From experiments such as these, neuropsychologists developed a much better understanding of the functions and abilities of the right hemisphere.[31] Although mute, it is by no means stupid, and it perceives and knows things that the left hemisphere does not. In general, this is the kind of knowledge that we categorize as intuitive. The right hemisphere excels in emotional and aesthetic perception, in the recognition of faces and objects, and in visual-spatial and constructional tasks. This scientific, rational evidence therefore supports our own personal, intuitive understanding of ourselves, and also supports the (often poorly articulated) view of artists and many designers that verbalization (i.e., allowing the left hemisphere to dominate) obstructs intuitive creation.

Anita Cross has drawn attention to the relevance of split-brain studies to improving our understanding of design ability.[32] One set of experiments which seems to be particularly relevant to design ability tested split-brain subjects on their recognition and intuitive comprehension of shapes and objects belonging to different geometrical classes.[33] No formal knowledge of geometry was required, but the shapes were presented in sets corresponding to euclidean, affine, projective, and topological geometries. Each subject was presented visually with five shapes in each set, and then asked to select from three further shapes, by touch only, one which belonged to the same set. On comparing the performance of left and right hands, the left hand (i.e., right hemisphere) was clearly superior. However, the superiority also varied consistently over the four geometrical categories, from euclidean, through affine and projective, to topological, suggesting that the left hemisphere becomes progressively less able to identify the more complex, subtle, and unconstrained geometries.

Several examples of the problematic behavior and perception of people with right-brain damage have been reported by Sacks, including "the man who mistook his wife for a hat" and who could not recognize a glove.[34] When Sacks held up a glove and asked "What is this?" the patient described it as "a continuous surface, . . . infolded on itself. It appears to have five outpouchings, if that is the word . . . A container of some sort." There is a weird logic to this reasoning, but no intuitive perception of the object and its obvious function. It is now known, therefore, that damage to the right hemisphere can impair brain functions that relate strongly to intuitive, artistic, and design abilities. This has been confirmed by studies of, for instance, drawing ability. One classic case is that of an artist who suffered right-brain damage.[35] Although he could make an adequate sketch of an object such as a telephone when he had it in front of him, he could not draw the same object from memory and resorted instead to reasoning about what such an object might be like. Studies of split-brain subjects have also shown, in general, that they can draw better with their left hands (even though they are not naturally left-handed people) than with their right.[36] Recognition of this right-brain ability has been put to constructive use in art education by Betty Edwards, who trains students to "draw on the right side of the brain."[37]

There is also, of course, a long history of studies in psychology of cognitive styles, which are usually polarized into dichotomies such as

convergent/divergent
focused/flexible
linear/lateral
serialist/holist
propositional/appositional

Such natural dichotomies may reflect the underlying dual structure of the human brain and its apparent dual modes of information processing. Cross and Nathenson have drawn attention to the importance of understanding cognitive styles for design education and design methodology.[38] This work has also been taken up by Powell and his colleagues in the design of information systems for designers.[39]

5. Design Ability Is a Form of Intelligence

What I have attempted to show is that design ability is a multifaceted cognitive skill, possessed in some degree by everyone. I believe that there is enough evidence to make a reasonable claim that there are particular, "designerly" ways of knowing, thinking, and acting.[40] In fact, it seems possible to make a reasonable claim that design ability is a form of natural intelligence, of the kind that psychologist Howard Gardner has identified.[41] Gardner's view is that there is not just one form of intelligence, but several, relatively autonomous human intellectual competences. He distinguishes six forms of intelligence: linguistic, logical-mathematical, spatial, musical, bodily-kinaesthetic, and personal.

Aspects of design ability seem to be spread through these six forms in a way that does not always seem entirely satisfactory. For example, spatial abilities in problem-solving (including thinking "in the mind's eye") are classified under spatial intelligence, whereas many other aspects of practical problem-solving ability (including examples from engineering) are classified under bodily-kinaesthetic intelligence. In this classification, the inventor appears alongside the dancer and the actor, which does not seem appropriate. It seems reasonable, therefore, to try to separate out design ability as a form of intelligence in its own right.

Gardner proposes a set of criteria against which claims for a distinct form of intelligence can be judged. These criteria are as follows, with my attempts to match design intelligence against them.

Potential isolation by brain damage. Gardner seeks to base forms of intelligence in discrete brain-centers, which means that particular faculties can be destroyed (or spared) in isolation by brain damage. The evidence here for design intelligence draws upon the work with split-brain and brain-damaged patients, which shows that abilities such as geometric reasoning, three-dimensional problem solving, and visual-spatial thinking are indeed located in specific brain-centers.

The existence of idiots savants, prodigies, and other exceptional individuals. Here, Gardner is looking for evidence of unique abilities which sometimes stand out in individuals against a background of retarded or immature general development. In design, there are indeed examples of otherwise ordinary individuals who demonstrate high levels of ability in forming their own environments—the "naive" designers.

An identifiable core operation or set of operations. By this, Gardner means some basic mental information-processing operations which deal with specific kinds of input. In design, this might be the operation of transforming the input of the problem brief into the output of conjectured solutions, or the ability to generate alternative solutions. Gardner suggests that "simulation on a computer is one promising way of establishing that a core operation exists." Work on the application of artificial intelligence to design is therefore helping to clarify the concept of natural design intelligence.

A distinctive developmental history, and a definable set of expert, end-state performances. This means recognizable levels of development or expertise in the individual. Clearly, there are recognizable differences between novices and experts in design, and stages of development among design students. But a clarification of the developmental stages of design ability is something that we still await, and is sorely needed in design education.

An evolutionary history. Gardner argues that the forms of intelligence must have arisen through evolutionary antecedents, including capacities that are shared with other organisms besides human beings. In design, we do have examples of animals and insects that construct shelters and environments, and use and devise tools. We also have the long tradition of vernacular and craft design as a precursor to modern, innovative design ability.

Susceptibility to encoding in a symbol system. This criterion looks for a coherent, culturally shared system of symbols which capture and communicate information relevant to the form of intelligence. Clearly, in design we have the use of sketches, drawings, and other models which constitute a coherent, symbolic media system for thinking and communicating.

Support from experimental psychological tasks. Finally, Gardner looks for evidence of abilities that transfer across different contexts, of specific forms of memory, attention, or perception. We have only a few psychological studies of design behavior or thinking, but aspects such as solution-focused thinking have been identified. More work in this area needs to be done.

If asked to judge the case for design intelligence on this set of criteria, we might have to conclude that the case is not proven. While there is good evidence to meet most of the criteria, for some there is a lack of substantial or reliable evidence. However, I think that viewing designing as a form of intelligence is productive; it focuses attention on design as a cognitive activity, it helps to identify and clarify features of the nature of design ability, and it offers a framework for developing further the case for designerly ways of knowing, thinking, and acting.

Conclusion

In this paper, I set out to develop an explicit understanding of the nature of design ability. I have outlined some defensive theories that might be built around the touchstone theory of the legitimacy of designerly ways of knowing, thinking, and doing. In particular, I have tried to show that design ability can appropriately be regarded as a distinct form of intelligence.

My broader aim, to which I hope this paper will contribute, is the establishment and development of a view of design as a discipline in its own right. This is a view shared by some of my colleagues in the invisible college of design studies, but is by no means a universally held view. For many people, design is and should remain an interdisciplinary field of studies. But that would mean that we design scholars would forever be dependent on other disciplines as our paradigms and sources. That surely cannot be a satisfactory state of affairs for us, and as Buchanan[42] and others have argued, we must work at and in our own discipline of design studies.

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4 Case-studies

- Roy, R., Case studies of creating in innovative product development. *Design Studies,* vol. 14, no. 4, 1993, p. 423-443.
- Candy, L., en E. Edmonds, Artefacts and the designer's process: implications for computer support to design. *Revue Sciences et Techniques de la Conception,* vol. 3, no. 1, 1994, p. 11-31.
- Cross, N., en Clayburn-Cross, A., Winning by design: the methods of Gordon Murray, racing car designer. *Design Studies,* vol. 17, no. 1, 1996, p. 91-107.

Een case-studie is een direct verslag van een enkel ontwerpproject. Case-studies leveren zo het ruwe materiaal van de ontwerpmethodologie: alle theorieën, modellen en technieken in een toegepaste wetenschap zullen zich tenslotte ergens op de praktijk van het vakgebied moeten baseren.
Case studies zijn voor ontwerpers geschreven ontwerpverhalen. Er wordt geen algemenere theorie afgeleid en, mits goed geschreven, lezen ze daardoor als een roman. De verhalen zijn voor ontwerpers aangenaam concreet, direct herkenbaar, inspirerend, fascinerend en leerzaam. Een goede case-study is een unieke kans om bij meer ervaren vakgenoten in de keuken te kijken.
Het ontbreken van theorie in case-studies heeft ook een paar nadelen: je zult niet zo sterk kunnen profiteren van de interpretaties en inzichten van een schrijver. De schrijver werkt bij case-studies slechts als doorgeefluik. Iedere lezer zal zelf zijn/haar eigen interpretatie van de tekst moeten maken, en iedereen zal er dus iets anders van leren. Dat is op zich nog niet zo erg, maar het kan gebeuren dat de lezer op een heel oppervlakkig niveau blijft steken, en weinig of zelfs helemaal verkeerde conclusies trekt.
Toch is het belangrijk in deze reader enkele case-studies te hebben: het blijven goede verhalen, die het waard zijn gelezen te worden. Het is wel zaak de opgedane ideeën eerst kritisch te bekijken en uit te proberen voordat ze als waar of nuttig worden overgenomen. Ook omdat een case-studie slechts één geval behandeld kunnen er eigenlijk geen algemene conclusies getrokken worden.

Het artikel van Robin Roy beschrijft de motivatie en werkwijze van twee zeer creatieve uitvinder-ontwerpers. Roy meent dat in de activiteiten van creative ontwerpers in het algemeen een bepaald patroon valt te herkennen.

In het tweede artikel, *Winning by design: the methods of Gordon Murray, racing car designer,* beschrijven Nigel en Anita Cross de ontwerppraktijk in een hooggespecialiseerde high-tech wereld. Het ontduiken en fantasievol interpreteren van de regels is duidelijk een van de grote inspiratiebronnen voor vernieuwing: een sluw uitgedacht veersysteem kan weer net dat beetje voordeel opleveren.

In het derde artikel, *Expert Designers,* trekken dezelfde twee auteurs een vergelijking tussen de manier van werken van Gordon Murray en van een andere ontwerper, 'Dan'. 'Dan' is een proefpersoon geweest in een zogenaamd Protocol Analyse-onderzoek. In een dergelijk onderzoek wordt een ontwerper gevraagd om hardop denkend een ontwerpopdracht uit te voeren, en wordt hij met videocamera's gevolgd in alles wat hij doet. Op deze manier kunnen we tot in detail bestuderen hoe een ervaren ontwerper nu eigenlijk ontwerpproblemen aanpakt.

Case studies of creativity in innovative product development

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Case studies of individual inventor/designers were developed in order to provide an insight into the creative process and an understanding of innovative product development. The cases provide information on the motivations of creative individuals, the sources of their ideas, their approaches to developing those ideas, their use of 2D and 3D modelling at different stages of product development, their need for domain-specific knowledge, and the value of tools such as creative thinking techniques and computer-aided design. The cases also illustrate some of the difficulties faced by British inventors and designers in commercializing innovative products.

Keywords: creativity, product design, product development, innovation

Case studies of creative designers and innovators can reveal much useful understanding and insight into:

- The product development process
- The role of creative thinking in product development, where creative design ideas come from and how they are developed into working products
- The problems faced by designers and inventors in getting novel products on to the market as commercial innovations

This paper examines some of these topics through case studies of creative individuals who have invented, designed, developed and introduced innovative products. The individuals and products are:

- James Dyson, an inventor, entrepreneur and product designer, and his innovative designs of a wheelbarrow and a vacuum cleaner
- Mark Sanders, a product designer and design consultant, and his novel design of a folding bicycle

In addition a brief comparison is made between these cases and similar examples of innovative mechanical products created by other individual inventor/designers.

These are cases of designers and innovators either working alone or in a small consultancy business and the focus is on how creative individuals conceive ideas and develop them. Nevertheless, the insights into the creative process provided by these cases are also relevant to the characteristics and practices of designers and engineers working in large R & D and design teams.

The case studies were developed using a similar research method. This first involved background research on the products and inventor/designers concerned, using published articles, patents, etc., followed by preliminary interviews with the individuals. Then in-depth interviews with the individuals were conducted. Finally, material gathered at the interviews – including promotional material, archive drawings and notes, photographs, etc. – was consulted and a further search for published information was made.

The case studies were originally prepared as educational material for an undergraduate Open University design course, entitled *Design: principles and practice* which was first presented in 1992*. Video programmes for this course were made using recordings made during the interviews. These videos and the full interview transcripts provided a valuable source of information for the material in this paper.

1 The case studies

The case studies presented in this section were chosen to help provide an understanding of the motivations of two creative inventor/designers; their sources of ideas; their different approaches to developing those ideas; their use of drawing and modelling at different stages of product development; their need for specific knowledge and expertise and their use of tools such as creative thinking techniques and computer-aided design (CAD). The cases also illustrate some of the difficulties faced by British inventors and designers in commercializing innovative products.

1.1 James Dyson – the Ballbarrow and Cyclone

James Dyson is an inventor and designer, trained at the Royal College of Art, who directs a small research, design and development company based near Bath. He is best known for two products; a wheelbarrow with a ball-shaped wheel called the Ballbarrow, and a novel type of domestic cleaner based on the cyclone principle, called the Cyclone or 'G-force'

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* Information about the course can be obtained from: The Course Manager, T264 Design: *principles and practice*, Faculty of Technology, The Open University, Milton Keynes MK7 6AA, UK

Figure 1 James Dyson with the Ballbarrow. (Photo: Mike Levers, Open University)

vacuum cleaner. The creative and innovative processes behind the development of these products is outlined below.

The Ballbarrow

Many innovative designs arise from a creative individual's dissatisfaction with, and desire to improve, existing products: what has been termed 'constructive discontent'. In this case it was Dyson's experience of using a conventional barrow whose wheel sunk into soft surfaces, whose body shape was poor for mixing cement and which was difficult to tip, that stimulated him to design the Ballbarrow (Figure 1). Dyson got the key idea for a ball-shaped wheel from his experience as a designer in an engineering company called Rotork, where he learned about balloon tyres

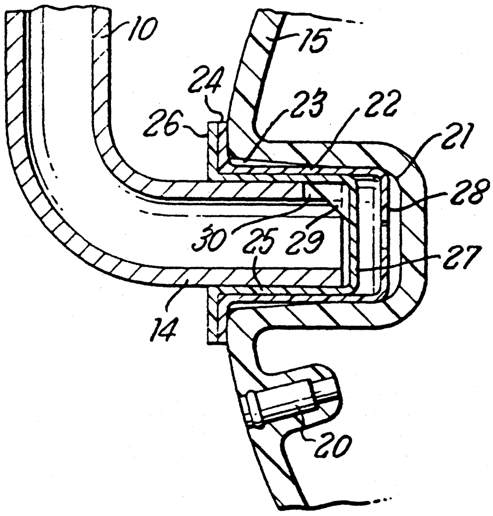

Figure 2 Details of the bearing to the ball-shaped wheel from the Ballbarrow patent. (Source: British Patent No 151011, 1975)

produced by rotational moulding for amphibious vehicles. This is a clear case of the *transfer* of an idea and technology from one application to another.

From this basic idea, Dyson developed the Ballbarrow concept, from initial sketches and drawings, to a prototype with a fibre-glass wheel moulded around a football, to patents and the finished design.

Dyson is an entrepreneur as well as an inventor/designer and always designs with manufacturing constraints and market potential in mind. With a relatively low investment in tooling required, he saw an opportunity to set up a business to make and sell the Ballbarrow.

Existing wholesalers and retailers of garden equipment did not think his novel design would sell and so Dyson initially marketed the Ballbarrow by mail order. He discovered that it sold well, even at about three times the price of conventional wheelbarrows. The Ballbarrow was launched in 1975 and after about four years Dyson sold the business to a major manufacturer. The Ballbarrow is still in production over fifteen years after its introduction and is now widely available through retailers.

The Cyclone vacuum cleaner

Dyson's next invention and enterprise arose from a production problem in the Ballbarrow factory. The resin powder used to coat the metal parts of the Ballbarrow kept clogging the filtration system. Dyson was advised to install an industrial cyclone (similar to that used to remove dust from the air in sawmills and other industrial plant) to separate the fine powder from

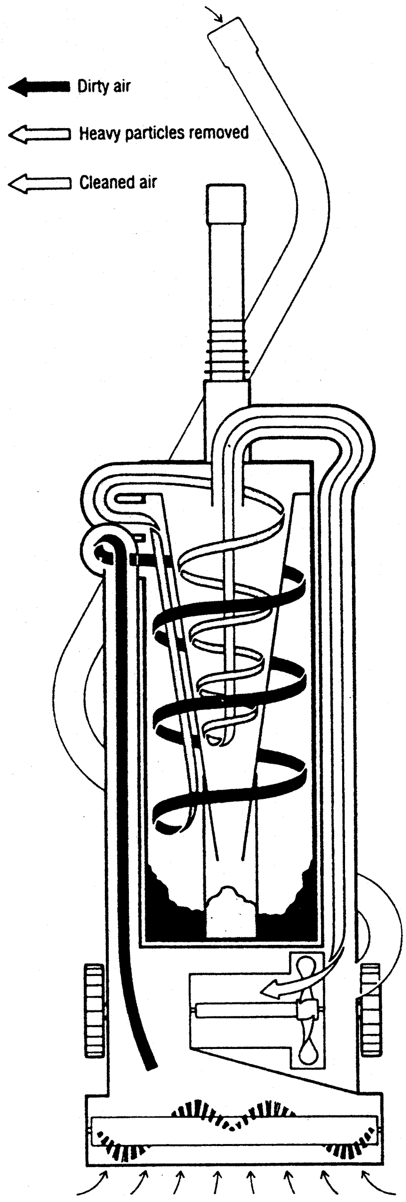

Figure 3 How the Cyclone vacuum cleaner works. A clean fan sucks in air through the head – or through the hose nozzle – (small arrows). Dirty air (black) enters the first stage cyclone at the top of the cylinder and swirls downward at increasing speed throwing dirt to the side, from where it falls to the bottom. Stripped of large dirt particles and most dust, less dirty air (grey) enters the second stage cyclone where fine dust is thrown to the sides and also falls to the bottom. Clean air (white) is expelled through the fan. (Source: Illustration by David Penny in Design Magazine *No 416 August 1983 p50 and* Engineering Design Education, *Spring 1985 p47)*

the air. While installing the cyclone James Dyson got the idea for a domestic cleaner that used the cyclone principle to separate the dust from dirty air (see Figure 3). Although it may be argued that the cyclone cleaner idea arose by chance, it is significant that Dyson is always on the lookout for such ideas and 'chance favours the prepared mind'. As with the Ballbarrow, Dyson's cyclone cleaner involved a mental *transfer* of technology from one application to another; 'we're never original', he observed, 'there are always connections somewhere'.

Figure 4 The Cyclone or 'G-force' vacuum cleaner (left) with concentric cyclones made in Japan by Alco International; Dyson's first prototype (centre) in which the cyclones were placed side-by-side and some of the several thousand models (right) used to develop the best shape of cyclone. (Photo: Robin Roy)

Dyson established the basic technical feasibility of his idea by testing a simple cardboard model cyclone fitted to a conventional vacuum cleaner. Dyson then considered the commercial potential of his invention before attempting to develop it. In this case tooling costs were likely to be high and it would therefore be necessary to license production to a major manufacturer. However, since vacuum cleaner technology had been static for years, he considered that the price of a radically new cleaner could be set sufficiently high for it to be a viable proposition.

Conceiving the basic idea behind the cyclone cleaner was, however, only the beginning of a lengthy research, design and development process. Determining the precise shapes of the cyclones needed to efficiently separate coarse particles and fine dust entailed Dyson in making and testing many thousands of brass, aluminium and perspex models in his workshop (Figure 4). He argues that this empirical 'cut and dry' approach was necessary because none of the theories about how cyclones worked could provide the answers he wanted. Nevertheless, other individuals might have attempted to model the cyclone mathematically before proceeding to empirical experimentation.

The first prototype, with two cyclones, one for particles and one for dust,

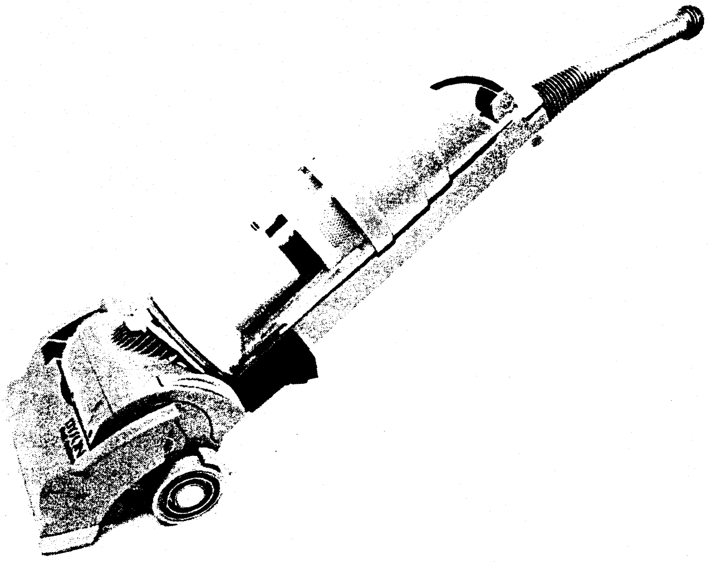

Figure 5 Dyson Dual Cyclone cleaner launched on the UK market in 1993. As with previous models the machine is brightly coloured (in this case yellow and gray) and the user is able to see the dust and dirt particles swirling in the transparent cyclone chamber (Photo: Dyson Appliances Ltd)

placed side-by-side was built in 1981 (Figure 4 (centre)). This innovative design was an upright cleaner that did not clog or lose power as it filled with dust, was easy to empty and had a built-in retractable hose to provide the functions of a cylinder vacuum cleaner. Its design involved Dyson's combination of skills as inventor, engineer and industrial designer.

Dyson showed his prototype cyclone cleaner to the two major UK manufacturers of vacuum cleaners. Although keen to see his invention, these manufacturers were not willing to licence it for production. Dyson believes that this rejection was partly due to the 'not invented here' syndrome and partly because such a radically new product represented too great a risk and challenge to the established technology. Undeterred, Dyson conducted further design and development work and produced a completely new design with concentric cyclones plus other improved features (the 'G-force vacuum cleaner' – see Figure 3 and Figure 4 (left)). He deliberately designed the product to be coloured pink to emphasise its innovativeness and made the cyclone enclosure transparent so that customers would be able to observe the swirling dust particles. 'From a market standpoint', Dyson argues, 'if the product contains any new ideas then it is absolutely essential that the product be visually different'.[1]

This design was successfully licensed in 1986 to a Japanese manufacturer after an abortive contract involving a British, an Italian and a US firm. The US firm subsequently copied the cyclone cleaner, which forced

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[1] **Dyson, J** Transcript of talk to The Bath Design Conference 1987 'Designer as Entrepreneur', 2–3 November, Bath, UK (1987)

Dyson into very costly patent litigation. In the early 1990s the 'pink vacuum cleaner' continued in production in Japan in limited numbers for design-conscious customers willing to pay about £1100 for the machine. However, by then Dyson had licensed another US firm to produce a cyclone cleaner called the 'Fantom' which was coloured black and sold at a more realistic price of about $300. In 1993 Dyson's company launched another new design of cyclone cleaner, the Dyson Dual Cyclone (Figure 5), in the UK. This was priced at £199, comparable to top-of-the-range conventional vacuum cleaners from the major manufacturers which had earlier rejected the cyclone concept.

Dyson's company has developed, or is designing, several other products using the cyclone principle, including a dry powder carpet cleaner, a wet-and-dry tank cleaner, a stick-shaped compact cleaner, a back-pack industrial cleaner and a device for removing particulates from diesel exhaust. Dyson is therefore using his invention as the basis for a whole family of designs.

Dyson's creative approach

Dyson combines the ability to conceive and develop technical inventions with the design skills to translate those inventions into attractive products. His particular approach to invention and creative design depends on getting ideas and solving problems when working with and observing physical objects (what Thring and Laithwaite[2] call 'thinking with the hands') rather than by drawing or theorizing. Dyson says he almost never solves problems by getting 'brainwaves in the bath', on the classic psychological model of creativity[3]; for him solutions come when 'welding or hammering something in the workshop'.

Dyson also believes that at the initial concept stage of an invention or new design it is best not to be too expert because the innovator has to question established ideas. However, in order to develop an idea into something that works and can be economically manufactured it is usually necessary to become highly expert technically. He observed: 'The more you get involved and study something in depth, the more creative ideas arise. You can't create marketable innovations as an amateur.' Fortunately, he finds that acquiring the necessary in-depth expertise is not very difficult when focused on a finite problem and specific area of knowledge.

Dyson's company makes extensive use of CAD running on personal computers for a variety of purposes, especially producing engineering and presentation drawings and analysing test results. Dyson does not regard CAD technology to be directly relevant to creative design, but it can

[2] **Thring, M W and Laithwaite, E R** *How to invent*, Macmillan, London, UK (1977)

[3] **Ochse, R** *Before the gates of excellence: the determinants of creative genius* Cambridge University Press, Cambridge, UK (1990)

liberate time formerly required for routine drawing and other tasks for creative work.

Thus, for Dyson, innovation is a matter of having good ideas based on experience and careful observation of the real world followed by hard work involving practical skills, technical expertise and design ability to convert that idea into a marketable product.

1.2 Mark Sanders – the Strida

The Strida is an innovative design of folding bicycle intended for short distance use and to link with other modes of transport. Mark Sanders designed the Strida while he was a mature postgraduate student on the joint Royal College of Art/Imperial College Industrial Design Engineering course (although he had been thinking about folding bicycles while working as a mechanical engineer before joining the course). As with the Ballbarrow the Strida arose from personal needs; Sanders was commuting from Windsor to London and felt that a folding bicycle would both meet his transport needs and provide a suitable college project.

Specification

Having decided on a folding bike, the starting point, as in most well-managed design projects, was a specification. The main points of the specification drawn up by Sanders, after reviewing the current state-of-the-art in folding bicycle design, are shown in the box on p 432.

Basic concept

What general form of folding bicycle would satisfy the specification Sanders had set himself? Often an idea for solving a problem will arise from an individual mentally 'immersing themself in the problem'. Sanders did this by spending a long time thinking about folding bicycles and jotting down ideas as they occurred. Realising that none of the existing types of folding bicycle were satisfactory, he turned for inspiration to other folding devices. The Maclaren baby buggy (a very successful design of folding childs' pushchair) led Sanders to the basic concept behind the Strida. This was a bike that would fold up, not into the smallest size possible, but like the buggy, into 'a stick with wheels at one end' (Figure 6). Like the buggy, such a bicycle could be carried in car boots, in buses and on trains. Here is a clear example of an *analogy* (in this case an object with a similar function) providing the basic concept for an innovative design.

Conceptual design

The next step was to find a configuration that would fold into the desired form. For this conceptual design stage Sanders again 'immersed himself in

[4] **Sanders, M A** 'The design of a new folding bicycle', unpublished Masters thesis, Imperial College/ Royal College of Art, London, UK (1985)

PROPOSED FOLDING BICYCLE[4]

A folding bicycle for short journeys with emphasis on low cost, simplicity and ease of use

Draft specification

1. *Cost:* low pricing essential i.e. retail about £100 [...]
2. *Foldability:* must be very simple and obvious, ideally taking less than 10 seconds
3. *Appearance:* must look simple (most folding bicycles look complex, a mass of tubes, spokes and cables); must look 'modern' and fashionable
4. *Original:* ideally a new configuration rather than a folding version of an existing configuration – patentable
5. *Ease of handling when folded:* must be easy to handle on public transport, without any sharp bits sticking out, and must fit in most car boots
6. *Weight:* must be light enough to be carried i.e. less than 25 lb
7. *Cleanliness:* must be clean and require minimum maintenance
8. *Additional features:* to appeal to both noncyclists and cyclists for short suburban journeys, possibly in conjunction with other forms of transport i.e. commuting

the problem' by making sketches of as many designs of folding bicycle as he could find in the literature and elsewhere and sketching new ideas as they occurred (Figure 7). Two basic configurations – an X-shaped and a triangular frame – emerged after two months researching, thinking and sketching. Alternative forms of these basic configuration with different folding and drive mechanisms were systematically checked against the specification on a matrix and the choice verified with the aid of simple wire models (Figure 8). Sanders chose the triangular frame configuration because it was novel and could therefore be patented. This choice was further checked by simple calculations on the loads and stresses in the frame members and by building an adjustable test rig from available cycle components to test the basic ergonomics and steering characteristics.

Detail design

Having established the basic configuration, more detailed aspects of the design had to be tackled. These also required considerable creativity.

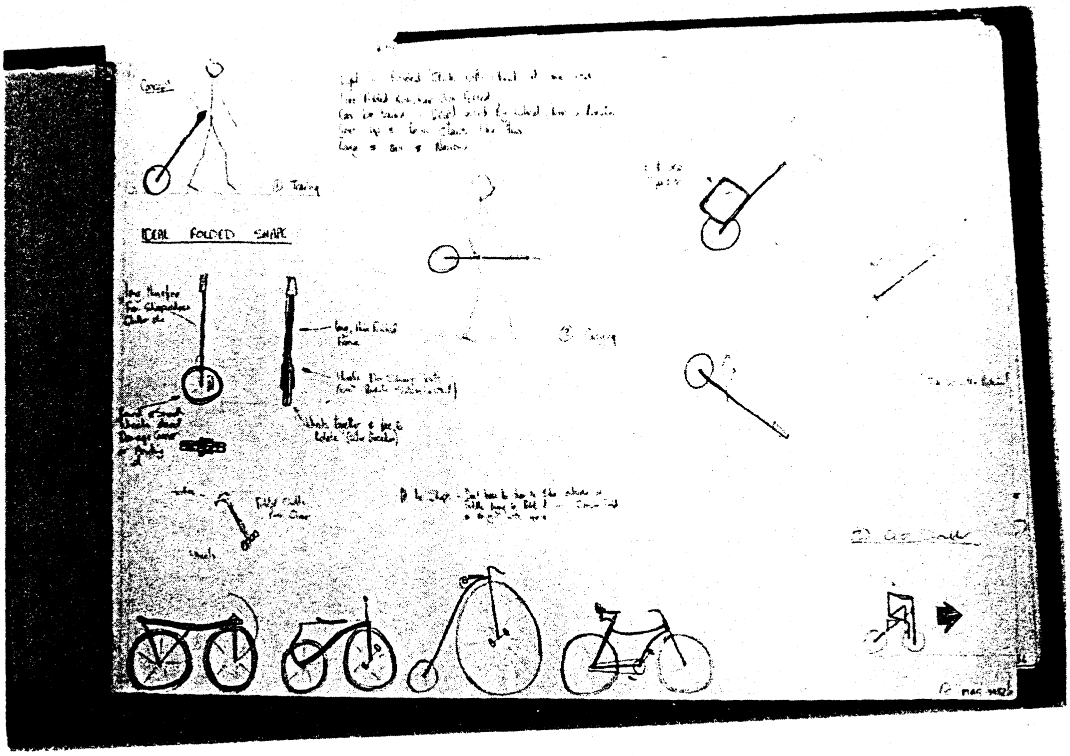

Figure 6 Page from Mark Sanders' first Bicycle Project Book showing the basic concept of a bike which folds into a stick with wheels at one end (Source: Mark Sanders)

For example, on the wire model (Figure 8) the triangular frame folded using a slider crank mechanism (the front end of the bottom tube sliding up the front tube). But for the wheels to fold together, this concept was abandoned in favour of the simpler solution of a joint between the bottom and front tubes.

Sanders conceived the design of the bottom and top joints by different approaches. The bottom joint design arose from thinking of other objects that easily disconnect. A car seat belt clasp provided the concept (Figure 9) – another clear example of *analogical* thinking in creative design. For the top joint Sanders was having difficulties with the mechanical design. So he turned to an approach of thinking visually, 'what would look good at the top of the triangle' from the viewpoint of the rider. This provided the inspiration which led to the design of a ball and socket top joint. As before, Sanders used sketching extensively to 'clarify and develop the ideas I was having in my head'.

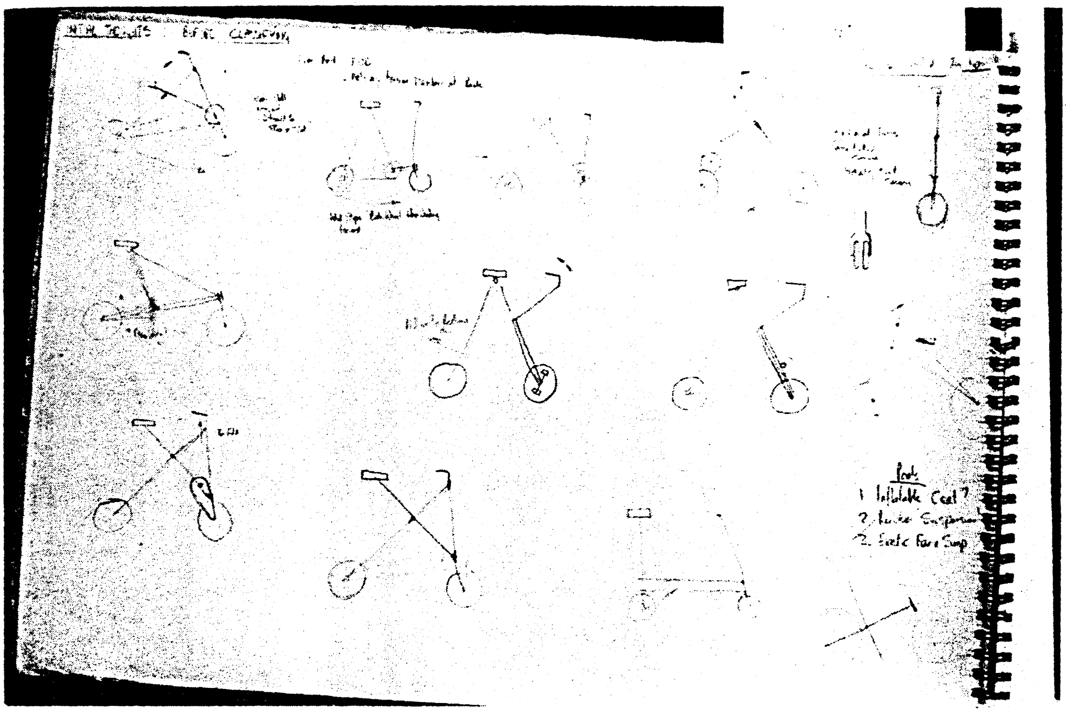

Figure 7 Page from one of Sanders' sketchbooks showing some initial design concepts. (Source: Mark Sanders)

After a lot of further detailed design work, including decisions on materials, calculations to check dimensions of components, etc., Sanders was able to patent his invention (Figure 10) and build the first working prototype.

Manufacture and marketing

Sanders attempted, unsuccessfully, to interest several manufacturers in making and marketing his patented folding bicycle. It was only after the first prototype was exhibited at the Royal College of Art degree show and featured in *The Sunday Times* in 1985 that manufacturers began to show interest. This led to an agreement with an entrepreneur who established a company to put the design into production.

The production version of the Strida has larger tube diameters than the prototype for extra stiffness and several prototype components were redesigned so as to be more economical to manufacture. The Strida has several unique features including a triangular frame constructed from bonded aluminium, a toothed belt drive and several plastics components (Figure 11).

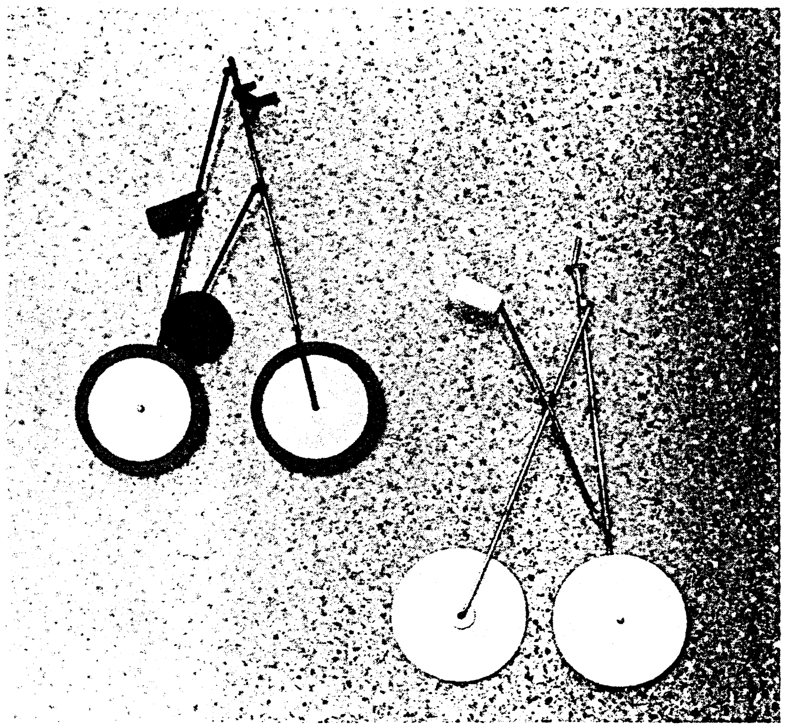

Figure 8 Wire frame models used to present and check the choice of X-shaped and triangular frame configuration. (Source: Mark Sanders)

The Strida was launched in 1987 at £189 and sold well in Japan, Italy, Germany and Scandinavia, but less well in the conservative UK market. The company marketing the (then Portuguese-manufactured) Strida ceased trading in 1992, after some 25 000 machines had been sold. The patents reverted back to Sanders, who then assigned them to the British Technology Group to licence to manufacturers around the world. Future production is most likely to be in Japan or the USA.

Computer-aided design

Since the Strida project Sanders has made considerable use of computer-aided design running on his personal computer. Although the original Strida was not designed using CAD, Sanders used his computer to produce the drawings for a steel-frame version, and the system Sanders owns could have been used to display animated 3D models of alternative frame configurations. This latter technique Sanders uses very effectively for other projects in his work as an independent design consultant. He views CAD as a tool that helps him rapidly explore, refine and present design ideas. It is most useful *after* the conceptual stage because the computer system is not so fast as sketching for exploring ideas.

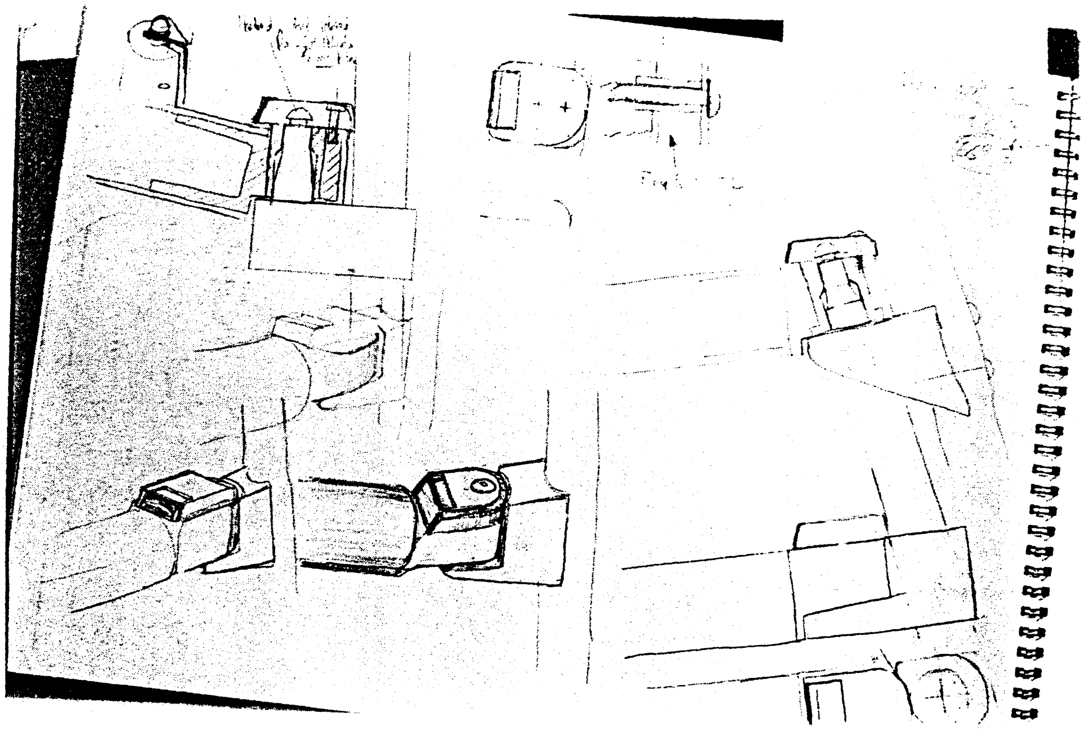

Figure 9 Page from one of Sanders' sketchbooks showing an exploration of ideas based on a car seat belt mechanism for the bicycle bottom joint. (Source: Mark Sanders)

Sanders' creative approach

Sanders, like Dyson, combines engineering and industrial design skills, but has a different approach to creative design. Key points of this approach include:

- 'Immersing yourself in the problem' at each stage in order to see if ideas from other areas or from nature (biological analogies) might offer a solution
- Gathering information from any likely source, including both specialist publications on the problem in question and general design or engineering reference books for ideas and information on related products, mechanisms, etc
- Sketching as 'a dialogue with yourself' or 'visual brainstorming' to get as many ideas as possible down on paper in order to 'clarify vague ideas in the head' and to move forward. The standard of drawing can be quite rough as the sketches are for personal use.

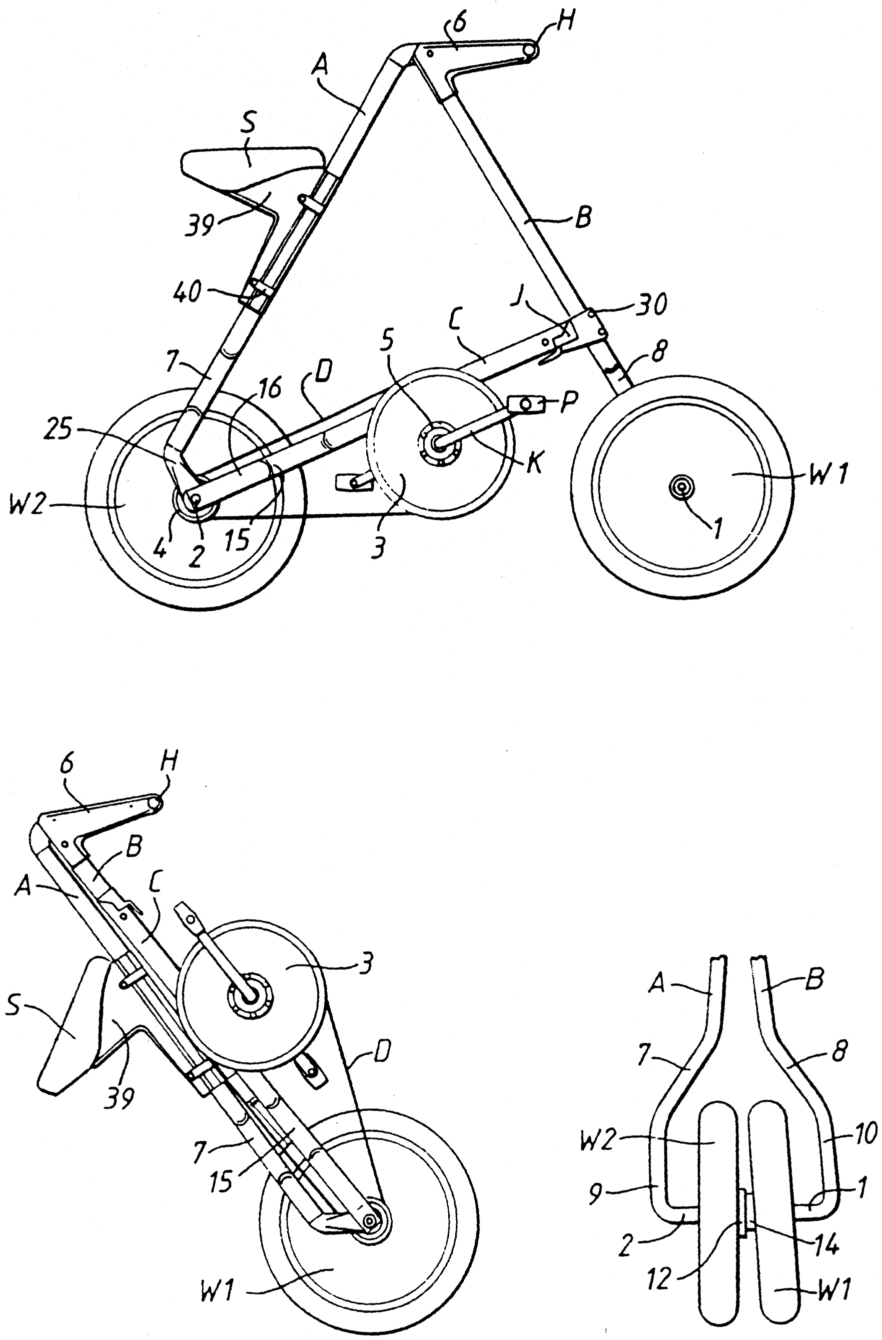

Figure 10 Patent drawings of Sanders' folding bicycle. (Source: Patent GB 2171656, 1986)

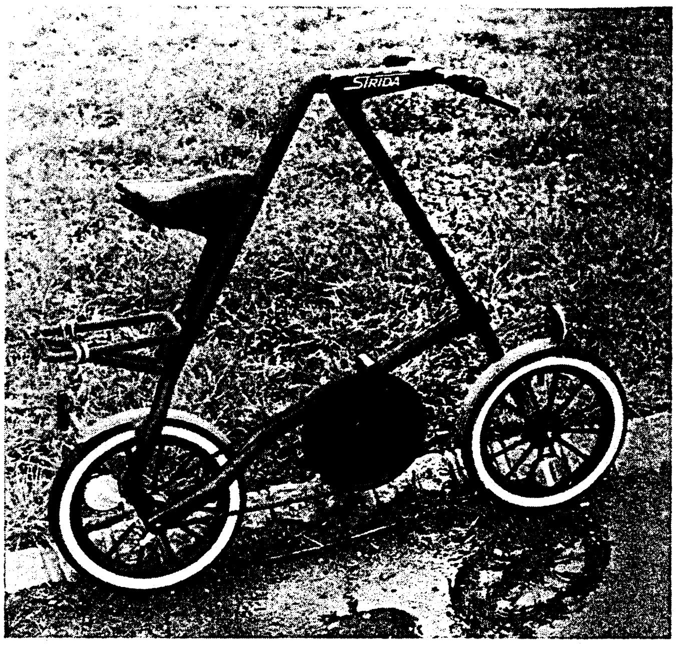

***Figure 11** Production version of the Strida folding bicycle. (Photo: Mike Levers, Open University)*

2 *Comparisons*

From these case studies of innovative product development it is possible to identify many similarities in and differences between: the product development process involved, the sources of creative ideas, the personal qualities of the individuals who produced the innovations, and the way in which the products were introduced to the market.

2.1 *The product development process*

The product development process followed a broadly similar pattern in the three cases, but with differences in the details depending on the nature of the innovation and the approach of the individual concerned.

Two projects arose from the personal need of the designer (Ballbarrow, Strida) and one from the chance occurrence of an inventive idea (Cyclone).

In all three cases the inventor/designers considered that their idea had commercial potential. However, in none of the cases was any formal market research conducted to assess the potential demand or to identify the requirements of potential customers. Indeed, Dyson argues that conventional market research, 'meaning asking people what they want is absolutely no use at all . . . it cannot predict how successful a radically new product is going to be'. Dyson contrasts conventional market research with his approach of *creatively* researching the market: 'seeing what other people are doing and why, getting market figures, analysing costings, shopping . . . travelling, study, by observing what is there and what isn't, new ideas are born'.[1]

In only one case (Strida) was a written specification for the proposed product drawn up. This is despite all the evidence about the importance of drawing up detailed market and technical specifications at the beginning of any product development project[5]. The lack of formal specifications is probably due to the fact that these were projects conducted by individuals working alone or in small organizations who may not have felt the need to write down a specification for communication to other people.

In all cases there was a *'primary generator'*[6], or essential generating idea, behind the invention or new design: a ball-shaped wheel, the cyclone principle, a 'wheels on a stick' folded form. This arose at the beginning, or at an early stage, in the project and provided the guiding concept for all the design and development work that followed.

Conceptual design involved testing the technical feasibility of this basic idea, using a mockup (Cyclone) and/or developing a configuration that could practically embody the concept, by sketching, or physical modelling (Ballbarrow, Strida).

As the projects moved from concept to development the processes diverged due to the different nature of the problems to be solved. Extensive empirical experimentation to verify and optimize the performance of an inventive technical idea was required in the case of the Cyclone vacuum cleaner before a working prototype could be constructed. Producing this prototype involved creating an overall design configuration to embody the technology plus detail design of components. In the other cases (Ballbarrow, Strida), no new technical principle was involved and so detail design of the components of a production prototype through sketching, engineering analysis, physical models and mockups could proceed once the overall design configuration had been established.

In one case (Ballbarrow) the design was relatively simple and could be established in sufficient detail at the prototype stage for materials to be specified, tools to be ordered and manufacture to commence. However, the Cyclone and Strida were more complex products and considerable further design and development work was required to convert the prototype to a product suitable for manufacture and sale.

[5] **Walsh, V, Roy, R, Bruce, M and Potter, S** *Winning by Design: Technology Product Design and International Competitiveness* Blackwell, Oxford, UK (1992)

[6] **Darke, J** 'The primary generator and the design process', *Design Studies*, Vol 1, No 1 (1979) pp 36–44

2.2 Sources of creative ideas

As these cases clearly show, creative ideas are needed not only to provide the basic concept for an innovative product but also to solve the many development and detail design problems involved in converting the basic concept into a commercial innovation. These creative ideas can come from many sources. The basic concept for both of Dyson's innovations arose from a mental *transfer* of technology from one application to another. Sanders, on the other hand, tended to seek *analogies* between the problem he was trying to solve and products or components with similar functions.

Although Sanders occasionally uses 'brainstorming with other people he knows well' when stuck for ideas, in general, such inventor/designers rarely employ formal creativity techniques. This may be because of their inate ability to generate new ideas, but Eugene Ferguson[7] has suggested a more important reason:

> More important to a designer than a set of techniques (empty of content) to induce creativity are a knowledge of current practice and products and a growing stock of first hand knowledge and insights gained through critical field observation of engineering projects and industrial plants.

It is not surprising therefore that in searching for ideas both individuals draw upon their prior knowledge and accumulated experience. However, both also recognize that it is almost always necessary to obtain further information from any accessible source. Where they may differ is in the timing and in their preferred method of thinking. For Dyson it is often better to be relatively uninformed at the early concept stage so as not to be hampered by prior solutions, but at the development stage to become a 'leading expert' in the particular area of the invention, whereas Sanders 'immerses himself in the problem' and existing solutions from the start. Dyson moves forward by working with physical models, mockups and prototypes and relatively little drawing, whereas Sanders uses sketching as his main means of problem exploration. What is clear from these cases is that innovative design is never an easy matter; it requires knowledge and expertise plus sustained and dedicated effort over a long period.

2.3 Personal qualities of innovators

It follows from the above that a high level of commitment to completing a given project, against all the obstacles that are bound to occur, is one very important quality of innovators. Both Dyson and Sanders combine skills in the technical aspects of design with the visual and human aspects, enabling them to develop products which appeal to customers as well as operating efficiently. Their concern for the commercial potential of an

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[7] **Ferguson, E S** *Engineering and the Mind's Eye* MIT Press, Cambridge, MA, USA (1992)

invention or new design, including the manufacturing constraints, is a safeguard against proceeding with ideas that have no hope of reaching the market. However, it is relatively rare to find such a combination of technical, visual and commercial skills in one individual and so in most cases a team effort is required to innovate.

2.4 *Commercial innovation*

Before reaching the market all three innovative products met with strong resistance from established UK manufacturers or retailers; they said the Ballbarrow would not sell; felt the Cyclone was too risky or radical; and expressed no interest in the Strida. Dyson had initially to set up a business to make the Ballbarrow himself and for the Cyclone was forced to find overseas manufacturers willing to license the invention. Sanders was fortunate to be approached by a British entrepreneur willing to invest in his bicycle. However, when that business failed he decided to assign the patents to the British Technology Group with manufacture in the Far East the most likely outcome.

To date probably the most commercially successful of the innovations is the Ballbarrow, which has been in production in various versions for many years. The other innovations have both been more successful in overseas markets than in the UK, especially in Japan where consumers appear more willing to adopt novel products.

2.5 *Comparisons with other innovations*

How typical are these cases of innovative products created by individual inventor/designers? The author has studied several similar cases[8], including the small-wheel bicycles designed by Alex Moulton[9] and the Workmate® workbench invented by Ron Hickman[10].

In these other examples too it is possible to observe:

- a 'primary generator' for the basic concept underlying the innovation (Moulton's belief in the advantages of small wheels for bicycles; Hickman's idea of making the work surfaces of a workbench function as a vice)
- The development of the design through physical models and prototypes
- High levels of creativity in designing key components (e.g. the suspension system of the Moulton bicycle, the vice mechanism of the Workmate)
- The initial resistance of existing manufacturers to the innovative product

[8] **Roy, R** Creativity and conceptual design: the invention and evolution of bicycles (Block 3 of OU course T264 *Design: Principles and Practice*), The Open University Press, Milton Keynes, UK (1992)

[9] **Moulton, A E** 'Innovation' *J. Roy. Soc. Arts*, (December 1979), pp 31–44

[10] **Hickman, R P and Roos, M J** 'Workmate' *CIPA J.* (Chartered Institute of Patent Agents), (July 1982) pp 424–457

- Commercialization first achieved by means of the inventor/designer setting up a business to make the product

3 *Conclusions*

Although it would be unwise to draw firm general conclusions based on these relatively few cases (mainly of mechanical innovations created by individual inventor/designers), a general pattern may nevertheless be observed.

Innovative products typically arise from personal need or direct experience of the individual inventor/designer, often as a result of using existing products and finding them unsatisfactory. A desire to improve upon existing artefacts is an aspect of the 'constructive discontent' displayed by creative individuals. Such individuals tend not to employ market research to identify customer needs in advance of the product development process, typically due to the view that a demand for radical new products cannot be properly assessed by conventional market research.

Inventors and designers tend to adopt a 'solution-focused' strategy[11] with an initial idea or 'primary generator' created early on which guides the product development process. This primary generator is often derived from the accumulated technical or design 'repertoire' of the individual, comprising knowledge of particular production processes or materials, admired or favourite products, and so on. This repertoire of knowledge and experience is far more useful than the numerous formal techniques that have been developed to foster creativity.

Inventors and designers typically employ a mix of 2D sketching and 3D physical modelling to conceive and then develop their inventions and designs. The mix will depend partly on the nature of the problem to be solved and partly upon the preferred working method of the individual. Whereas some individuals may rely heavily on what Ferguson[7] has called 'thinking sketches' to clarify and develop the visual ideas held in the mind's eye, others rely much more on observing and working with physical models. Mathematical analysis and CAD systems tend to be employed mainly to check and refine ideas and decisions. Indeed, there is a general tendency among such creative individuals to move quickly from ideas, calculations, sketches and drawings to physical models and prototypes. The eminent engineering designer, Alex Moulton[12] has commented:

> Ideas and calculations must be translated into drawings and sketches [. . .] drawings must be made into hardware as soon as possible, so that reality can be tested and analysed. This is the most important part of the development cycle.

[11] **Lawson, B** *How Designers Think* Architectural Press, London, UK (1980)

[12] **Whitfield, P R** *Creativity in Industry* Penguin Books, Harmondsworth, UK (1975)

Translating an innovative idea into a product ready for manufacture, is a difficult process involving long periods of dedicated work, the solution of many subproblems in component design, and often several setbacks. Creativity is required *throughout* product development, not just at the early concept stage. Although specialist knowledge may not be required to conceive the basic idea behind an innovation, domain-specific knowledge and technical and design expertise are almost always required to go beyond the idea to develop a workable product. Moulton[13] has observed:

> What differentiates the designer, who successfully innovates, from the crackpot inventor is the depth of study. Certainly I have made [. . .] dozens of 'inventions' leading to patents; but they all arise from a revelation emanating from observing and studying in a particular field; never from a random idea occurring in a random field.

Attempts by an individual inventor/designer to interest established UK manufacturers in producing a highly innovative product seem likely to be unsuccessful; probably due to the 'not invented here' syndrome, the unwillingness of such manufacturers to take risks, or other organizational factors. Successful innovators therefore require the entrepreneurial skills to find alternative sources of support and investment, often from overseas, and/or to establish a business to manufacture their product themselves. Established UK manufacturers may subsequently wish to adopt the innovation, but usually only after it has proved to be a commercial success in the market. These cases therefore seem to lend weight to the argument that creative British inventors and designers are more likely to have their ideas commercialized by overseas manufacturers. Attitudes to innovation and risk need to change if UK (and European) industry is to benefit from the undoubted creative talent of British inventors and designers.

4 *Acknowledgments*

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[13] **Moulton, A E** 'Design and technological innovation', Paper given to the Design Congress 'Profit by Design', (1966)

Winning by design: the methods of Gordon Murray, racing car designer

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This is a case study of the working methods of one particularly successful designer in a highly competitive design domain, Formula One racing car design. Gordon Murray was chief designer for the very successful Brabham and McLaren racing car teams in the 1970s and 1980s. His record of success is characterized by innovative breakthroughs, often arising as sudden illuminations, based on considering the task from first principles and from a systemic viewpoint. His working methods are highly personal, and include intensive use of drawings. Personality factors and team management abilities also appear to be relevant. There are some evident similarities with some other successful, innovative designers.

Keywords: innovation, creativity, design process, racing car design

Several studies have appeared recently of creative and innovative designers[1–3]. These studies of designers add to the more general studies of creative individuals in science, art and engineering[4]. The motivations for such studies include improving our understanding of the psychology of creative behaviour, identifying features of creative behaviour that it might be possible to develop through educational processes, and developing models of the creative design process.

The particular study reported here is of an engineering designer who has established a long and distinguished record as a highly successful and highly innovative designer in a highly competitive environment, Formula One racing car design. Gordon Murray joined the Brabham racing car team as a young designer-draughtsman in 1971, and was appointed chief designer in 1973. Brabham cars designed by him were driven by Nelson Piquet to win the World Championship in 1981 and 1983. In 1986, he moved to the McLaren Formula One team as technical director, and again his car designs, driven by Alain Prost and Ayrton Senna won the World Championship in 1988 and 1989. Gordon Murray then became technical director of McLaren Cars Limited, an offshoot of the racing team, and

1 **Lawson, B** *Design in mind*, Butterworth Architecture Press, Oxford, UK, 1994

2 **Roy, R** 'Case studies of creativity in innovative product development' *Design Studies* Vol 14 No 4 (1993) pp 423–443

3 **Candy, L and Edmonds, E** 'Artefacts and the designer's process: implications for computer support to design', *Revue Sciences et Techniques de la conception* Vol 3 No 1 (1994) pp 11–31 (see also their paper, 'Creative design of the Lotus bicycle', in this issue of *Design Studies* pp 71–90

4 **Ochese, R** *Before the gates of excellence: the determinants of creative genius*, Cambridge University Press, Cambridge, UK (1990)

0142-694X/96 $15.00 *Design Studies* **17** (1996) 91–107 0142-694X(95)00027-5

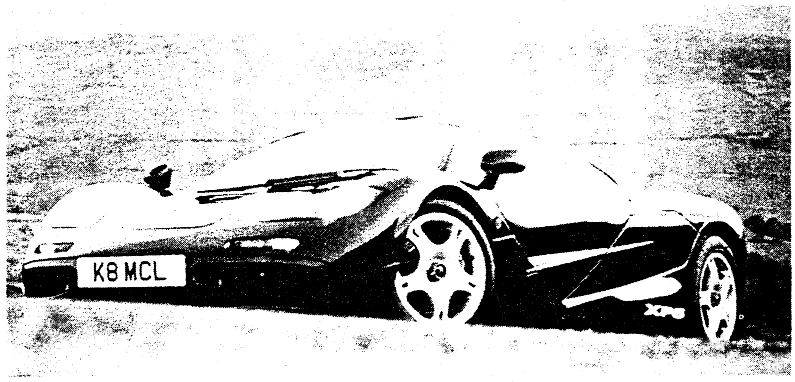

Figure 1 The McLaren F1 (McLaren Cars Ltd.)

became responsible for the design and development of a completely new, road-going 'super car', the McLaren F1, which has attracted immense attention as the 'ultimate' motor car. In 1995, GTR versions of the F1 were produced for competition in sports car races: at the 1995 Le Mans 24-hours race, McLaren F1s came first, third, fourth and fifth.

This paper is based on several informal conversations with Gordon Murray, and a more formal, taped interview specifically for this study. Our purpose in preparing this study was to seek insights into the design processes of someone who has a long history of being a successful, highly-innovative designer.

1 Formula One designing

Formula One racing car design is, of course, significantly different from almost every other kind of design domain. Gordon Murray likens it to war. Engineering and technological development in wartime is the closest analogy to Formula One he can think of, with resources – human, financial and technical – being poured into the design and construction of machines that must have, and maintain, vital performance edges over those of the enemy. Throughout the nine-month Formula One season there is a battle to be fought on a different field every two weeks, with a new campaign starting again every year.

There are also, of course, the 'rules of engagement' for this perpetual 'war': the Formula One technical and sporting regulations, which minutely and precisely specify the physical and operational limits within which the teams must compete. Gordon Murray regards the regulations (the constraints) of racing car design, along with its intense pressure and competition, as fundamental to the necessity to innovate. With every team working within the same constraints, only innovation, coupled with constant refinement and improvement, can provide the competitive edge.

In other design fields, as he has discovered, the lack of regulations can be slightly bewildering, allowing the designer to wander at whim in a more loosely-bounded solution space.

Innovative design, Gordon suggests, comes down to people and their environment. 'It comes from the environment and the situation you're in; you're governed by these regulations; you're in this sort of a war situation; and you're desperate to try and think of things all the time – alongside all the normal design (improvement) processes which are more laborious . . . I can't tell you how hyper it is, relative to architecture, bridge design, furniture design . . .'

2 *Designing radical innovations*

Throughout a racing season there is constant, relentless pressure on the designer to keep making design improvements. But there is a limit to what can be achieved with any car design, before a jump has to be made to basically a new design, an innovation. As Gordon Murray says, 'Given the situation and the pressure at any one time, you do get to the brick wall . . . I mean you're doing all these normal modifications, you know you can't go any quicker, you need to make the step forward.' The constant pressure during the racing season breeds a fervour to succeed that never stops, Gordon says; 'You gotta go quicker, gotta go quicker.' The pressure then to come up with something new becomes intense, and the responsibility is all yours, 'and you get more and more sort of – panicky, almost.'

The situation can only be resolved by a new car design. In many instances, and for most teams, this will be a new version of the previous season's car; perhaps a new chassis, new suspension, or new engine to be accommodated; perhaps a change in regulations to be met. For Gordon Murray it would often mean trying a radical new concept. In the midst of the pressure, the fervour, the panic, he 'used to get breakthroughs, I mean I used to get like suddenly a mental block's lifted.' These breakthroughs would come as a sudden illumination: 'I know it's a cliché, but I did have a lot of good ideas in the bath, I really did.' The illuminations came, again in classical form, after long periods of preoccupation with the problem, and after what Gordon Murray emphasizes as the most important factor in innovative design, of reconsidering the problem situation from first principles; he stresses the need to 'keep looking back at fundamental physical principles.'

Another crucial factor is the motivation to carry-through the bright idea into detailed implementation. Again, intense pressure, even in the brief close season, ensures that ideas that look certain to be winners will be pushed through to detailed implementation with the same fervour as in the racing season. Other possibly good ideas are discarded on a rapid evaluation of their implications for a car's weight, performance or handling. In racing car design, it is not just a matter of having ideas, but of really implementing ideas that are going to improve performance – of having to 'do it', as Murray says; 'You have the idea, but you have to do it, and that's what cuts the bullshit out.'

2.1 *Framing the problem*

At the start of the 1981 season, the Formula One governing body, FISA, introduced new regulations intended to reduce the 'ground effect' on racing cars. This effect had been pioneered on Lotus cars some three seasons earlier; smooth underbodies, side skirts and careful aerodynamic design provided a ground-effect downforce which increased the car's grip on the track surface. This meant much higher cornering speeds were possible, and by the 1980 season people were worried about the g-force effects that were being imposed on the drivers. FISA banned 'sliding' skirts from the start of 1981, but allowed fixed skirts and set a minimum ground clearance of 6 cm. For Gordon Murray this sudden change in regulations was a stimulus to innovation.

> 'The 1981 car, which was a World Championship winning car, came absolutely from the regulation change. You sit there and you read the regulations and think, how we are going to do it? How the hell can we get downforce back? What (the regulations) said was "At all times the car will have a 6 cm gap between the bodywork and the ground . . . and there can be no driver-operated device to change that gap." . . . And everybody looked at it, and built cars with 6 cm gaps . . . And I looked at it and I thought, if that 6 cm gap could be a 1 cm gap I could double the downforce on the car; and it's going to go down to a 1 cm gap at some point, like (under braking) at the end of the straight. So if I can make a physical thing – something that involves physics again – that drives the car down on its own, and holds the car down on its own without any mechanical aid or button or electronics or anything, it's legal. So in three months we developed a hydropneumatic suspension.'

Gordon Murray's thinking on this – and he says it came as a sudden illumination – was that the authorities had to accept that at some points during a race, any car's ground clearance is going to be less than the 6 cm minimum simply because of the effects of braking, or roll on corners etc. Knowing that any driver-operated, mechanical device to alter the ground clearance was illegal, he focused on the physical forces, the 'bits of nature', that act on a car in motion. The braking and cornering forces he felt unable to work with because of their asymmetrical effects on the car, but the downforce from air pressure on a moving car could, if the car was correctly designed aerodynamically, push the car down equally over its whole length and width. The design challenge, therefore, was to let the natural downforce push the car down at speed, and then somehow to keep it down when it slowed for corners, and then allow the car to return to 6 cm clearance at standstill.

The ingenious solution which Gordon developed incorporated hydro-pneumatic suspension struts at each wheel, connected to hydraulic fluid reservoirs. As the car went faster, the natural downforce pushed the body lower on its suspension and the hydraulic fluid in each suspension strut was pushed out into the reservoirs. The trick then was to find a way of letting the fluid return to the suspension struts only very slowly when the car slowed down. At corners, the suspension would stay low, but on slowing down and stopping at the end of the race, the fluid would return from the reservoirs to the suspension struts, giving 6 cm ground clearance.

> 'So I rushed around and looked at the technology of micro-filters, mainly in the medical industry . . . they were using these organic micro-filters which let the fluid through themselves but very, very, very, slowly. And we built the world's tiniest throttle valve with one of these filters in it, and a tinly little pin – we were using drills that you couldn't even see! We went and quickly developed what size hole we needed, so that it took a lap to push the fluid through these little holes – all naturally with the downforce – pushed the fluid into the reservoirs and the car was stuck on the ground, running with its skirts virtually touching the ground. And because it took so long for the fluid to get back through the same valves and filters, it held the car down there, and after the race you have the slowing down lap . . . and the car just slowly came back up. Nothing to do with the driver at all, just physical forces! And we went to the first race in Argentina and just blew everybody into the weeds, just totally; and everybody went bananas!'

Other teams protested that the Brabham cars must have been fitted with a driver-operated device. It was obvious that the cars were lower during racing than they were in the pits, but, of course, the scrutineers could find no illegal device. Under pressure from the other teams, the authorities pointed out that the Brabham cars were clearly lower than 6 cm when out on the circuit, which contravened the regulations, but Gordon countered that, at various points so was every other car. To stop the protests, he suggested to the authorities that every car should have its underbody painted, and at the end of the race every car which showed that at some point the the underbody had rubbed the ground should be disqualified; and of course the other teams would not accept this.

For some time the other teams experimented hapharzardly with varieties

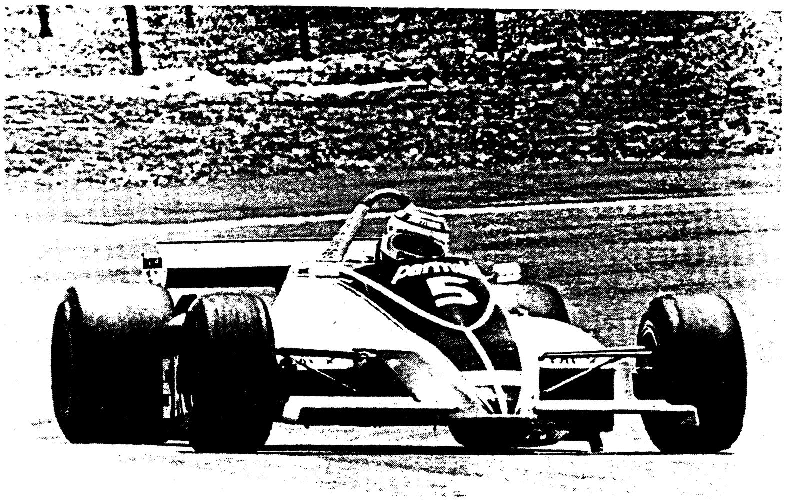

Figure 2 The Brabham BT49C, driven by Nelson Piquet to the World Championship in 1981 (Hazleton Publishing Ltd.)

of hydropneumatic suspension systems, to Gordon's amusement; but, very frustratingly for him, just a few races later in the season, FISA reversed its stance and allowed driver-operated switches for controlling suspension height.

The hydropneumatic suspension system was an example of an innovation initiated by a change in regulations which forced Gordon Murray's thinking onto how to retain the ground-effect advantage. It is an example of radical innovation, through framing the problem in a new way, and having the motivation to follow through a basic idea into finely detailed implementation.

2.2 *Systemic design*

As another example of radical innovation, Gordon Murray refers to the Brabham team's introduction of planned pit stops during a race, in the 1982 season. This was not so much a radical innovation in the car design *per se*, but reflects more a total systems approach to the overall goal of winning each race. At that time it was not normal to have pit stops as regular, planned parts of the race routine. Pit stops were for emergencies such as changing a punctured or badly-worn tyre. For Gordon Murray, the innovation of introducing planned pit stops was part of an overall strategy arising from taking his thinking back to a basic issue – how to make the car lighter. As part of that strategy, he pursued the idea of running the car with only half the normal, full-race fuel load, and including a pit stop for refuelling. But that was only the starting-point for a thorough investigation of the implications of such an idea, and of working-through the detailed implementation.

Nowadays, Formula One pit stops have been refined down to an incredibly quick norm of about six or seven seconds actual stopped time, in which time all four wheels are changed and up to 130 litres of fuel taken on. The total racing time lost is perhaps some 20 seconds. In 1982, Gordon Murray calculated that if the total racing time lost by a pit stop was less than 26 seconds, there could be sufficient advantage gained elsewhere to make it worthwhile.

There were many factors that came into calculating the advantage. Obviously, the lighter the car is, the faster it is – not only in straight-line top speed but also in accelerating and decelerating. Half-size fuel tanks also have an advantage over full-size ones in that the weight distribution is lower, the roll-couple on corners is lower, and is more constant throughout the race. Tyre wear, and the complicated choices of harder or softer tyre compound, also becomes a critical factor, because a lighter car can run on softer compounds which improve cornering speeds. Even the psychology of racing came into it, because a car with obvious advantages in the early part of a race could lead other competing drivers into pushing their cars harder, causing them more tyre wear, or into taking more risks. For all the objective, measurable factors, fine calculations were made, leading to the conclusion that a pit stop had to lose less than 26 seconds racing time to be worthwhile.

At that time, a quick pit stop for tyre changes took about 15 seconds of actual stopped time. Gordon Murray calculated that he had to get this down to about 10 seconds and to reduce as much as possible the slowing-down and warming-up times. An extraordinary development programme had to be undertaken in an incredibly short time.

> 'From having the first idea to having a pit-stop car running and doing a test was three or four weeks – and that's all the time that you have. So you would take each individual thing and tackle it. Say, OK, how can we get 35 gallons into the car in 10 seconds? The only way you're ever going to do it is using pressure, and then you have a crash programme to develop a system. . . . That's what is great about race car design, because even though you've had the big idea – the 'light bulb' thing, which is fun – the real fun is actually taking these individual things, that nobody's ever done before, and in no time at all try and think of a way of designing them. And not only think of a way of doing them, but drawing the bits, having them made and testing them.'

Within three weeks, they had thought of, designed, made and tested a pressure-fed refuelling system which delivered 100 litres into the car within 3 seconds. To improve pit-stop procedures, Gordon hired a film crew to film the team practising pit stops, and then played back the film, stopping it to identify difficulties and errors, and devising ways to improve the procedures. Such improvements included details such as redesigning the wheel-nut gun to improve its engagement with the nut. The new systems, the improvements, and the training of the pit team got the actual stopped-time down to under the target of 10 seconds. One 'big-killer' remained: 'When you put new tyres on they were cold, and it always took two laps to get back up to speed, and the time you lost in those two laps killed the whole thing. So then I thought, well I know the tyres start working at 70°C . . . so we designed an oven, a wooden oven with a gas-fired heater, and we heated the tyres up – and 10 seconds before the car was coming in we opened the oven door, whipped the tyres out, put them on, and the guy was instantly quick. Now every Grand Prix team has tyre heating; that's where it started.'

The example of the introduction of the 'pit-stop car' illustrates how a radical innovation was driven by the competitive urge to find a significant advantage within the constraints of the regulations; how a total systems approach was adopted; how the basic, 'light bulb' idea had to be precisely evaluated; and how implementation had to be carried through to fine levels of detail. The new pit-stop approach was first tried by the Brabham team during the 1982 season, on the Brabham BT50 car. For the 1983 season, Gordon Murray designed his new 'half-tank' car, BT51, only to be faced with an unexpected change of regulations affecting the car's 'skirts' (which helped produce the 'ground effect'), so that another crash programme had to be initiated to design the BT52. With this car, and with the help of pit stops, Nelson Piquet won the Formula One World Championship again in 1983.

2.3 *Designing from first principles*

Gordon Murray insists on keeping experience 'at the back of your mind, not the front' and to work from first principles when designing. For instance, in designing a component such as a suspension wishbone, 'it's all too easy – and the longer you're in design the easier it is – to say, I know all about wishbones, this is how it's going to look because that's what wishbones look like.' But if you want to make a step foward, if you are looking for ways of making it much better and much lighter, than you have to go right back to load path analysis. It is like designing things for the first time, rather than the *n*th time.

As one example of his approach to designing from first principles, Gordon refers to a small, and perhaps seemingly insignificant part of the McLaren F1 road car – the steering column. 'Conventionally, it would have been, right, steering columns are typically three-quarter-inch solid steel bars.'

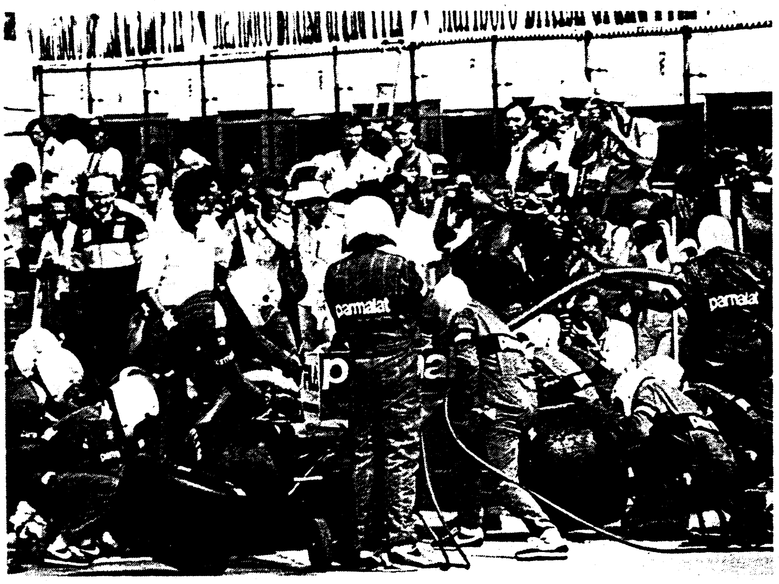

Figure 3 Gordon Murray (white shirted, centre left) supervises a pit-stop for Nelson Piquet to change tyres and take on fuel during the 1983 British Grand prix (Hazelton Publishing Ltd.)

This conventional solution arises because the column not only has to carry torsional forces from the resistance to the turning wheels but also bending loads from the driver leaning on it whilst getting in and out of the car. It also has conventional points of support, is mounted in rubber bushes to reduce noise, and it ends up being encased in a plastic housing for reasons of appearance and convenience. But it does not provide the sort of direct steering feel that a racing driver needs, and the McLaren F1 is supposed to be a driver's car.

So Gordon decided to apply racing design principles, starting by separating the needs to carry both torque and bending loads. However you design the steering column itself, you still need a cover to house electrical cables and to mount switches, 'so if you've got to have that anyway, why not use the insect principle where the skeleton's on the outside, and make that the structure that takes all the bending forces?' This thinking led to the design of the steering column itself as an aluminium tube of just 1 mm wall thickness; 'it's only taking torque and it weighs nothing.' The steering rack is cast integrally with the bulkhead, so that there can be no relative movement. The support bush is right behind the steering wheel rather than down at the dashboard, and the system is now lighter but stronger than a conventional solution, and also has the right racing feel. The redesign process stemmed from considering first principles – separating the torque and bending loads – and from an imaginative breakthrough – using the housing cover for structural purposes as well as appearance.

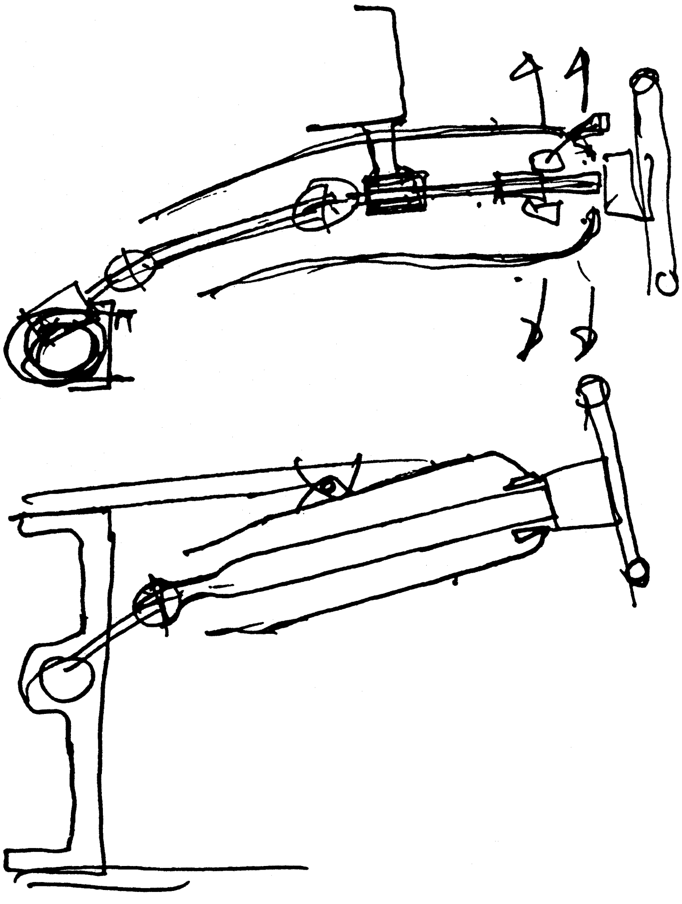

Figure 4 Gordon Murray's explanatory sketch of the design thinking behind the steering column of the McLaren F1, comparing conventional steering column design (top) with that of the F1 (bottom)

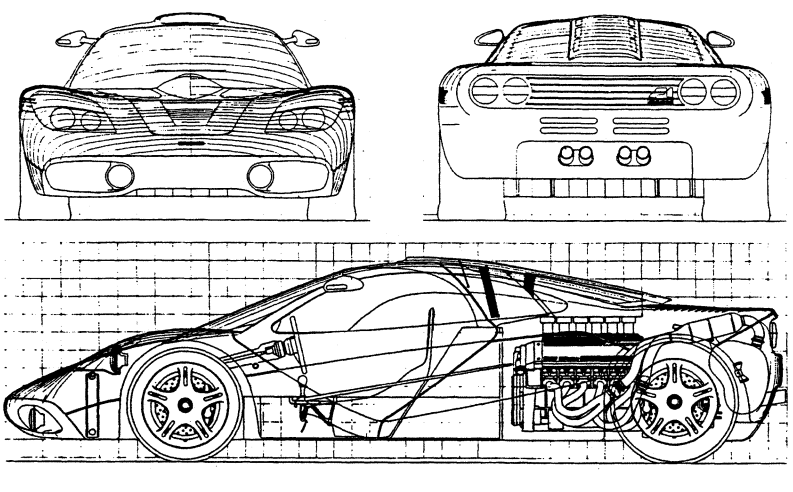

Figure 5 Front, rear and side views of the McLaren F1, the side view part transparent to show details such as the steering column (McLaren Cars Ltd.)

2.4 *Learning from failures*

Not all of Gordon Murray's racing car design innovations have been successes; he has had a share of failures, too. One of his largest failures was the 'surface cooling' car, the Brabham BT46 of 1978. This radical concept was meant to be several 'steps forward' at once; reduction in weight, improvement in driver safety, and what was meant to be a long-term technical advantage over the opposition. His imaginative idea of 'surface cooling' was to do away with normal radiators for cooling the engine, and instead to pass the water and oil through surface heat exchangers built integrally into the monocoque structure: the 'skin' of the car was both structure and radiator. Other refinements included improved monocoque form, elaborate electronic engine and lap-time instrumentation systems for the driver, carbon fibre brake discs, and an on-board air jacking system for quicker tyre changes.

There were innumerable detailed implementation problems with the surface cooling features, and trials soon showed that surface cooling was not going to work. Gordon Murray says, 'I knew why it didn't work, but before the first race we just literally ran out of time.' So a revamped version of the BT45 was quickly rushed out. It had been a very expensive failure.

Another innovative design that failed was the last one Gordon Murray designed for Brabham, for the 1986 season. This car was designed to be as low as possible, with the driver virtually lying flat. It involved also putting the engine into a lying-over position from the vertical, and this was the feature that proved not to work. 'We just could not get the lay-down engine to scavenge the oil properly, and we kept losing a lot of horsepower.' Later, at McLaren for the 1988 season he was able to develop the same concept more successfully. 'I did a lay-down McLaren, exactly what we did at Brabham but with a Honda engine that worked, and we won 15 out of 16 races. So you do have things that don't work; but in that case it wasn't the idea that didn't work, I just ran out of time and money, and I took on much too much in a very short period to get it to work properly.'

3 *Design process and working methods*

In explaining his approach to innovative design, Gordon Murray stresses the need constantly to work from 'first principles.' Working from first principles, and working in a highly organized way seem to come naturally to him, but his personal design process is much less structured than the results might suggest. Although he can tightly organize his team and run a complex racing organization, his personal ways of designing are relatively unstructured, based on annotated, thumb-nail sketches. 'I don't sit down and say, OK, now I've had the idea, let's see, this is a solution, these are the different ways to go, if I do this, and do that . . .; I do lots of scribbles just to save it, before I forget.'

Gordon's design process is based on starting with a quick sketch of a whole idea, which is then developed through many different refinements. 'I do a quick sketch of the whole idea, and then if there's one bit that looks good, instead of rubbing other bits out, I'd put that bit to one side; I'd do it again and expand on the good bit, and drop out the bad bit, and keep doing it, doing it; and end up with all these sketches, and eventually you end up throwing 90% of these away.' He also talks to himself – or rather, writes notes to himself on the sketches; notes such as 'rubbish', 'too heavy' or 'move it this way 30 mm.' Eventually he gets to the stage of more formal, orthographic drawings, but still drawing annotated plans, elevations and sections all together, 'Until at the end of the day the guys at Brabham used to call them 'wonder plots', because they used to say 'It's a wonder anybody could see what was on them'!

Although Gordon Murray carried immense personal responsibility for the design work of his racing cars, inevitably it involved a lot of teamwork. Clearly he has been successful in inspiring others to work with him. He likes to involve team members in the design problems, and for that reason prefers to recruit all-rounders to his team; 'I never have engineers that aren't designers.' He also likes to work collectively, standing around a drawing board discussing problems and trying ideas.

For this kind of teamwork, and especially for conceptual design work, he finds computer-aided design systems too restrictive. For the McLaren Fl super-car, he installed a 5 m long drawing board in the design office, so that the car could be drawn full size. 'The problem with CAD for this sort of stuff is that you can never have a full-size drawing, unless you do a print, and by the time you do a print it's out of date in the concept stage.' He also does not like the one-person emphasis of CAD screens; 'You can only ever talk to one person at once – you stand behind and look over somebody's shoulder, which is not very good for a boss–designer relationship anyway, to have somebody standing behind you is never a good thing. To look over somebody's shoulder at a tiny little screen, it's just wrong, it's totally wrong.' On the other hand, he fully acknowleges that tasks like a complex suspension plot to determine the wheel envelope are ideal for CAD.

As for managing a team, he regards it as treading a fine line between dictator and diplomat. He knows exactly what he wants to achieve, but he likes being able to have people around 'to bounce ideas off.' He prefers being able to hand-pick a team, and to give his people enough freedom and responsibility to feel that they are really making a worthwhile contribution to the team.

4 *Comparisons with other studies*

A number of similar studies of highly creative or innovative designers has been published in recent years, and several points of similarity emerge. Lawson[1] interviewed 10 highly successful, creative architects. One thing that emerges strongly from his studies that resonates with this study of Gordon Murray is the architects' use of drawing as a design aid. Lawson observed that, 'Frequently, drawings are overlaid and mixed together. Two-dimensional plans or sections can be seen with sketches and more diagrammatic marks all on the same piece of paper in what appears a confusing jumble.' These sound like Gordon's 'wonder plots'. The architects also use their drawings as a means of thinking 'aloud', or 'talking to themselves', as Gordon put it. For example, Lawson reports the architect Richard MacCormac as saying, 'I use drawing as a process of criticism and discovery'; and the engineer-architect Santiago Calatrava as saying, 'To start with you see the thing in your mind and it doesn't exist on paper and then you start making simple sketches and organizing things and then you start doing layer after layer . . . it is very much a dialogue.'

The common elements in these similar descriptions are the use of drawing not only as a means of externalizing cognitive images but also of actively 'thinking by drawing', and of responding, layer after layer and view after view, to the design as it emerges in the drawings. It is the reliance on drawing, and the preference for the immediacy of the interaction and feedback that manual drawing gives, that makes the architects, like Gordon Murray, unenthusiastic about CAD as a conceptual design tool.

Lawson also draws attention to similarities in the working methods of the architects he studied, which we can see also have similarities with Gordon Murray, such as the need to maintain periods of intense activity, but interspersed with periods – usually away from the normal work environment – of more reflective contemplation. Lawson's architects also are characterized by a dedicated sense of purpose, which they share with small, highly motivated teams of coworkers. There is also a sense of focusing on, or framing a problem so precisely that it can be approached from 'first principles'; as Santiago Calatrava said: 'It is the answer to a particular problem that makes the work of the engineer . . . you need a very precise problem . . .'

Roy[2] studied two innovative industrial designers, one of whom, James Dyson, reported that (unlike Gordon Murray) he almost never solved problems by getting 'brainwaves in the bath', but more often when doing some practical work, 'welding or hammering something in the workshop'. However, this practical work may in itself be a way of letting the mind relax. Two of James Dyson's most well-known design innovations, the 'Ballbarrow' wheelbarrow and the 'Cyclone' vacuum cleaner, both came from practical experience and from drawing on technology transfer from other fields (rather like Gordon Murray's example of transfer of filter technology from medicine). The 'Ballbarrow' drew from his experience with balloon tyres on amphibious vehicles, and the 'Cyclone' drew from his installation of an industrial cyclone to remove fine powder from the air of the factory where the 'Ballbarrow' was being produced. For both of the designers studied by Roy, James Dyson and Mark Sanders, technology transfer appears to have been instrumental in their innovative thinking, together with personal motivation and deep immersion in the problem area.

A study of highly innovative engineers by Maccoby[5] was based on interviews with eight such people, nominated by their peers. One of the observations Maccoby makes especially is the 'systems approach' adopted by these innovative engineers: 'The innovator has a systems mind, one that sees things in terms of how they relate to each other in producing a result, a new gestalt that to some degree changes the world.' Again, this sounds similar to the approach adopted by Gordon Murray. Maccoby continues with an example which might also be describing Gordon's approach: 'For example, one can think about a car in terms of all its parts working together to make it go . . . In contrast, most engineers do not think in systems terms. They are concerned about designing a good piece-part, like a clutch.' This sounds like Gordon describing how his approach is different from conventional, piece-focused, engineering design.

Maccoby also identifies the life-long commitment of the innovators he studied, extending back to examples of interests stemming from their childhood or youth; the fact that innovators are not put off by failure, but expect to learn from failure; and that they have 'the courage to innovate'. He also points to several examples amongst these innovators of their experience of solutions arising from sudden illumination of problems that they had been worrying about. For example, like Gordon Murray's bathtime insights, the engineer-inventor Jacob Rabinow reported that 'flashes of inspiration come to him while shaving, driving, or partaking in other activities. Solutions are usually sudden.' Not all the innovators

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[5] **Maccoby, M** 'The innovative mind at work', *IEEE Spectrum*, December 1991, pp 23–35

reported examples of sudden illumination, and for some, solutions only come from continuous hard work, but it is clear that sudden illumination (of a prepared mind) is a frequent element in creative thinking.

Another study of an innovative designer, by Candy and Edmonds[3], is particularly relevant because it is also based upon the design of race-winning competition vehicles. Candy and Edmonds studied the design process of the racing-bicycle designer, Mike Burrows. His innovative, carbon fibre, 'monocoque' design of 1985 was at first banned by the cycle racing authorities, but later became the basis of the LotusSport Olympic pursuit bicycle on which Chris Boardman won the 4000 metres individual pursuit in world record time at the 1992 Olympic games. Interestingly, there are many features of Mike Burrows' design approach that are very similar to that of Gordon Murray.

Like Gordon Murray, Mike Burrows is an enthusiast for his sport, and has participated as a racing cyclist. They both therefore have a very high personal motivation that drives their work, and both are steeped in the knowledge and expertise of their domains. They both constantly keep abreast of progress and current developments in their own and related fields, simply out of personal commitment, and this can often lead to insights and the transfer of technology from one field to another. The use of analogical thinking, a systems view, and total immersion in the problem are also identified as features of Mike Burrow's approach by Candy and Edmonds. A significant difference in working methods, however, is Mike Burrow's limited use of sketching as a design medium; he prefers to move quickly to immediate physical realizations of ideas in models and mock-ups. Nevertheless, his successful approach to the 'monocoque' cycle design reflects Gordon Murray's approach of concentrating on a major objective and designing from 'first principles'. In Mike Burrows' case it was a concentration on pursuing the dominant principle of minimizing aerodynamic drag, and being prepared to completely reconceptualize the conventional bicycle frame.

It is also interesting and relevant that Buijs[6] used the example of another racing car designer – Jim Hall, the American Indy-car designer – to illustrate his suggestion that creative innovation occurs in 'jumps' from one level to another in the spiral of learning. Buijs likens the jump to a change in paradigm, based on a new conceptualization of 'the problem'. The new concept arises from a single-minded vision of how to achieve or maintain a competitive advantage. The examples of Jim Hall's innovative designs are very close to our examples of Gordon Murray's innovations: for instance, his introduction of aerofoil wings, and especially his intro-

[6] **Buijs, J** *Innovation and vision', in D Colemont, P Grøholt, T Rickards and H Smeekers (eds) Creativity and innovation*, Kluwer, Dordrecht, The Netherlands, 1988, pp 57–62

duction of undercar fans to 'suck' the car onto the track surface, which, as Buijs points out, was also something tried again later on Brabham cars, designed by Gordon Murray.

5 *Conclusions*

There appear to be sufficient striking similarities between this study of the racing car designer Gordon Murray and other studies of innovators and creative designers for us to be able to draw some conclusions about common features of a successful approach to innovative design.

In particular, there are some potentially useful observations to be made about the methods and approaches adopted by successful, innovative designers, which might perhaps to some extent be transferrable to others. Firstly, there is the approach to defining or framing the problem to be solved. The goal is set at a high level, with clear objectives, and in direct terms which might even seem to be simplistic. It is this simple clarity which might make other people conclude that the goal is simply impossible. There is a holistic, systems view of the problem encapsulated in the goal. A clear concept of how to reach this goal is devised – sometimes by means of a sudden insight which comes when relaxing after deep immersion in the problem – and the solution details then cascade from the concept. Intense work is needed to develop, evaluate and refine the solution details, creativity is still '1% inspiration and 99% perspiration'. The clear, generative concept is not simply 'found' in the problem as given, but orginated by the designer; it is not a matter of pattern recognition, but of pattern creation. This pattern creation process stems from conceptualizing in terms of the 'first principles' of the defined problem area.

This approach seems to require, or is synergistic with, a particular style of working. Some aspects of this style arise from the innovative designer's personality characteristics, for instance, their personal motivation means that they are steeped in their chosen domain, and they are prepared when necessary to work obsessively at their chosen problem and solution. The working style is based on periods of intense activity, coupled with other periods of more relaxed, reflective contemplation. This working style may not be a reflection of a particular personality trait, but a necessary aspect of creative work, which requires alternating intense effort with relaxation. The innovative designer also likes, perhaps needs, to work with a small team of committed coworkers who share the same passions and dedication.

The working methods of the innovative designer are, for the most part, not systematic; there is little or no evidence of the use of systematic methods of creative thinking, for example. The innovative designer seems to be too involved with the urgent necessity of problem solving to want, or to need, to stand back and consider their working methods. Their design approach is more strategic than tactical. An important feature of their strategy is parallel working, keeping design activity going at many levels simultaneously. The best cognitive aid for supporting and maintaining parallel design thinking is drawing. Drawing with the conventional tools of paper and pencil gives the flexibility to shift levels of detail instantaneously; allows partial, different views at different levels of detail to be developed side by side, or above and below and overlapping; keeps records of previous views, ideas and notes that can be accessed relatively quickly and inserted into the current frame of reference; permits and encourages the simultaneous, nonhierarchical participation of coworkers, using a common representation. The drawing of partial solutions or representations also aids the designer's thinking processes, and provides some 'talk-back'. As well as drawing, innovative designers frequently like to undertake practical work related to the design solution, such as building models or mock-ups, or participating in construction.

We hope that these conclusions might offer guidance for those involved in the management of design activity or the development of methods or tools to support design activity, for those involved in design education, and for designers themselves.

6 *Acknowledgment*

We are, of course, indebted to Gordon Murray for the time and attention he gave to explaining his working methods to us.

Expert Designers

Nigel Cross & Anita Clayburn Cross

Abstract

Progress in design methodology will be restricted, or proceed in inappropriate directions, if studies of designer behaviour are limited to studies of novice or average-ability designers. We have studied two outstanding expert designers and are able to draw some parallels between their design strategies. We note that they both take a systemic view of the design situation, choose to frame their view of the problem in a challenging way, and draw upon first principles to guide both their overall concept and detailed design. Our observations are in line with those of studies of expert performance in other creative fields.

1. Introduction

Although teamwork is increasingly the dominant mode of design activity, many instances still occur of design practised almost solely by one individual. Even within teams, one individual may be nominated as the 'chief designer', or may spontaneously take on such a role through an apparently natural level of design ability. It is also the case that many highly creative or talented individuals become successful and highly-regarded designers, with international reputations both within and beyond their professional peer groups. The reality of design practice seems to be that some individuals have outstanding design abilities.

Nevertheless, most studies of designer behaviour have been based on novices (e.g. students) or, at best, designers of relatively modest talents. This is because it is easier to obtain such people as subjects for study. However, if studies of designer behaviour are limited to studies of rather inexpert designers, then our understanding of design ability will also be limited. This will in turn limit our potential for developing models of design activity, and restrict progress in the whole field of design methodology. Studying expert and even 'outstanding' designers may give us different, and more appropriate, insights and understanding of design activity, on which to develop models and methods of design.

There have been only a few studies of outstanding designers, such as Lawson's [1] studies of successful architects. In this paper, we report briefly on our own study of an outstanding designer – the racing car designer, Gordon Murray – and we make a new analysis of the strategies of the expert designer 'Dan', who was a subject of the 1994 Delft Design Protocols Workshop. In this analysis, we develop parallels between Dan's design strategies and those of Gordon Murray. We find several striking similarities, which suggest that general lessons may be constructed about the nature of expertise in design. Such lessons could be important steps towards raising general standards of design across the professions and towards improving design education and the nurture of design expertise.

3. Expert Designer 2: 'Dan'

We propose to compare the design strategies of Gordon Murray with those of a designer who, though not such an internationally famous designer, is nonetheless another highly successful, outstanding designer. This second designer is 'Dan', the subject used in the 1994 Delft Design Protocols Workshop. Dan is an engineering designer with over twenty years' experience of designing both mechanical and electro-mechanical machines, and robotic systems and devices. He was one of the earliest designers of robotic devices, and he has won several design awards from the American Society of Mechanical Engineers.

Dan was video-recorded whilst he 'thought aloud' during a 2-hour experimental session in which he was asked to design 'a carrying/fastening device that would enable you to fasten and carry a backpack on a mountain bicycle'. Our observations of Dan's design strategy are therefore based on the artificial situation of a controlled, protocol analysis experiment. Full details of the experiment (and several other analyses of Dan's design activity) are reported in the Workshop proceedings [3]. Although he is highly experienced, the design task set in the experiment was, nevertheless, a novel task for Dan.

In the following analysis of Dan's strategy, quotations are taken from the transcript of his 'think aloud' comments, preceded by the timestamp for the quotation. The substantive experimental session began at timestamp 00.15minutes.

3.1 Rapidly Gaining Experience

A distinctive feature of the strategy followed by Dan was the time and effort he put into gaining an overview of the potential solution space; his aim appeared to be to determine the most feasible section of that solution space in which to begin work. This was a deliberate strategy, which he explained in 'think-aloud' comments such as:

> (00.21)
> there's no sense in starting from scratch if you can start at square two instead of square one
>
> (00.27)
> my general philosophy is don't try to reinvent the state of the art if it already exists

The early part of Dan's strategy is concerned with getting 'up to speed' – with informing himself of the nature of similar, rival products to that which he is designing, with identifying a section of the solution space where he is likely to generate an acceptable solution, and therefore with avoiding starting to work in areas that are likely to be unfruitful.

This strategy of 'starting from square two' – i.e. building on the experience of others – might appear to be borrowing from old ideas rather than initiating a new design. However, what Dan was doing seemed to be more like immersing himself as rapidly as possible in the domain of expertise relevant to the (for him) novel design task that he had been set. He was prepared to devote rather a lot of time to this – some 30 minutes were spent on gathering this kind of information, and a further 15 minutes were spent confirming and coming to the conclusion that the best location for the carrying device would be over the rear wheel of the bicycle. So at least 45 minutes of the 2-hour design session were spent getting up to speed, so that he would hit the ground running when he did start actual design work.

Most of this early information was gathered from a potential rival company already making bicycle luggage carriers. Dan gathered information from the company's catalogue and from a telephone call to the company. The catalogue information was scanned for general principles – the weight and cost limits of the rival products, and their mounting positions on the bicycle – as indicated in these comments:

(00.28)
aha, so he has a series of front mounting racks and rear racks, and he sells these things at between . . thirty dollars and fifty dollars

(00.29)
his frames weigh between . . 480 grams and . . 650 grams

(00.30)
he has more rear racks than front racks . . they are all frames that mount over the wheel

The telephone call was also used to gather general principles and expert advice about the preferred location on the bicycle for carrying a backpack. Dan commented as follows about what he learned from the telephone call:

(00.44)
I learned a few things; I learned about the fact that people originally thought that it was bad to have it on the front but if you keep the backpack pretty low on the front it's OK, high up is bad; on the rear the issues are related to heel clearance and thigh clearance, and he feels that keeping it as low as possible is good

So Dan appeared to be searching not for prior design examples *per se*, but for the criteria (such as weight and cost) that his design would have to match, and for experience that would guide the major design decision of whereabouts on the bicycle to locate the carrying device. In this way, Dan rapidly developed valuable, surrogate expertise in this novel design domain.

3.2 Systemic Design

As an expert designer, Dan also displayed aspects of his design approach that can be compared with those of an outstanding designer such as Gordon Murray. Firstly, Dan developed a systemic view of the problem he had been set. Very early in the session, reading the design brief, he made a comment that suggested he saw something special about the design problem:

(00.19)
it is to attach to a bicycle, a mountain bike and to me that makes it different

Dan was also able to draw on personal experience that helped him to formulate some of the implicit requirements for a good design solution:

(00.26)
having used a backpack on a bike in the past and having ridden over many mountains, unfortunately not on a mountain bike but I can imagine that the situation is similar, I learned very early on that you want to keep it as low as possible

He also drew upon personal experience to confirm that the preferred location for the backpack would be on the rear wheel rather than the front wheel:

> (00.51)
> my first thought is hey the place to put it is back here; there's another advantage by the way of having it in the back I can see immediately, and that is it's off the side in the front, and you're on a mountain bike trail and you hit something you're out of control in the front wheel
>
> (00.52)
> downhill work on mountain bikes, I know you want to keep your weight back rather than forwards

Dan's personal experience of biking with a backpack led him to identify an issue that only someone who has had such experience might be aware of:

> (00.55)
> when I biked around Hawaii as a kid that's how I mounted my backpack . . . and I have to admit if there's any weight up here this thing does a bit of wobbling, and I remember that as an issue

So the systemic view that Dan formed of the problem was that of the total task that encompasses the dynamic system of the rider plus bicycle plus backpack, and the issues of control of the bicycle that arise in the situation of riding over rough terrain with a heavy backpack attached to the bicycle. This is a different situation from that of everyday, smooth-surface, level-grade riding, and it accentuates the need to position the backpack low and to the rear. The view that Dan had of the design task was significantly different from a view that might be formed from considering the bicycle and backpack in a static situation, or without considering the effects on the rider's ability to control the bicycle with a mounted backpack. Dan's understanding of the dynamic situation therefore enabled him to formulate a systemic view of the design task.

3.3 Framing the Problem

The second aspect of Dan's approach that can be compared with that of Gordon Murray is how he 'framed' the problem. From a systemic overview of the total dynamic situation of rider + bicycle + backpack, Dan identified stability as a key issue. Quite early in the session, commenting on the prototype design that had been developed earlier by other designers, he surmised about the user-evaluation report on this prototype that:

> (00.22)
> it probably . . says the backpack's too high or something like that, and that bicycle stability's an issue

Dan therefore seemed to frame the problem as 'how to maintain stability', given that a heavy backpack had to be carried over the rear wheel of the bicycle, and given his experience of the 'wobbling' that can occur in the riding situation. This problem-framing and his prior experience led him to conclude that he must design a rigid carrying device:

> (00.59)
> the biggest thing that I remember in backpack mounting is that it's got to be rigid, very rigid

He then developed this viewpoint into the requirement that the structural members of any carrying device must be stiff:

> (01.06)
> making the carrier stiff enough for holding the backpack, that seems to be a big issue

So, at about halfway through the session, Dan had arrived at a framing of the problem which directed him to design a stiff, rigid carrier, mounted as low as possible over the rear wheel. Soon after, a secondary framing viewpoint emerged, which seemed to arise from considering the client's needs as well as those of the user (which had dominated Dan's thinking so far). The client for the design task was a manufacturer who wanted to sell the carrying device in conjunction with an already-existing backpack. The device therefore needed to have unique selling points that differentiated it from other, similar products. During the development of his design concept, Dan kept in mind that he needed the product to have a 'proprietary feature', as emerged from some of his comments, discussed below.

3.4 Designing from First Principles

The third aspect of Gordon Murray's approach as an outstanding designer that we identified was his concern with designing 'from first principles'. Dan also showed this aspect, as he developed his concept design for the carrying device. A 'first principle' that Dan identified and followed was that a triangulated structure is inherently rigid. This led him to avoid designing a rectangular, parallelogram form of structure, which was the form that rather naturally seemed to arise from considering the basic shape of the carrier and the location of its supporting structure on the bicycle. Whilst drawing Figure 1(a), Dan commented:

> (01.07)
> one of the problems with a bicycle carrier where the frame is mounted out here and it goes to that, is that you end up with a parallelogram; bad thing, bad thing!

He expanded on this comment, identifying his concern with stability as a key requirement:

> (01.08)
> if I were to make a frame that looked like this, that would be a very poor design because basically what I've got is, I've got a parallelogram which has very little lateral stability

He then introduced the 'first principle' of triangularity, whilst drawing the triangular form on to Figure 1(a):

> (01.09)
> it would be nice if I could, for instance, run these rods up here to some point and therefore create a triangle, this would give me great stiffness – good idea!

The 'first principle' of triangularity subsequently guided Dan's generation of the basic form and the detailed design features of his carrier. As he drew his design in more detail (Figure 2), he commented:

> (01.16)
> we're going to have this as a triangular structure here to provide the lateral stability

And as he developed the design he constantly referred to structural principles, seeking to avoid 'bad' configurations and to generate 'good' ones, making comments such as:

> (01.42)
> my detail here is going to have to be something like this because my forces along this tube are this way . . good, this is good; and then this detail is going to be, er, let's see . . alright that's bad . . that's bad . . that's bad, so I'm going to need something like that

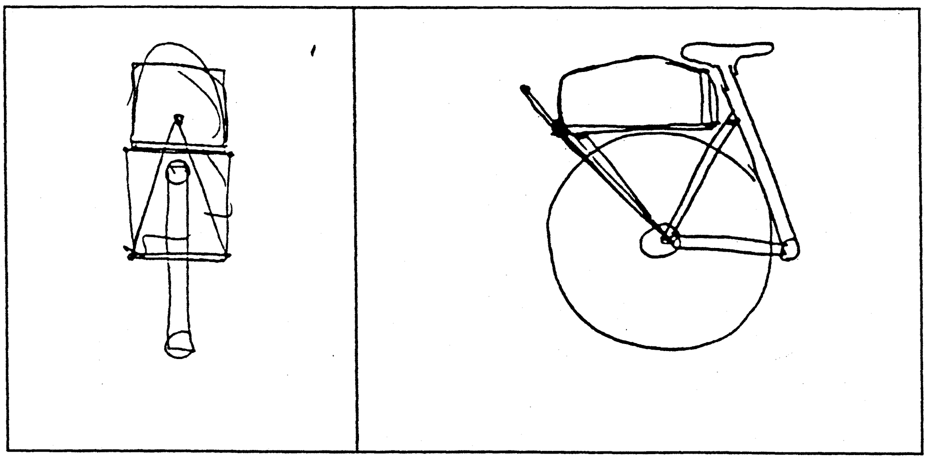

Figure 1: Dan's sketches of rear and side views of the bicycle and carrying device.

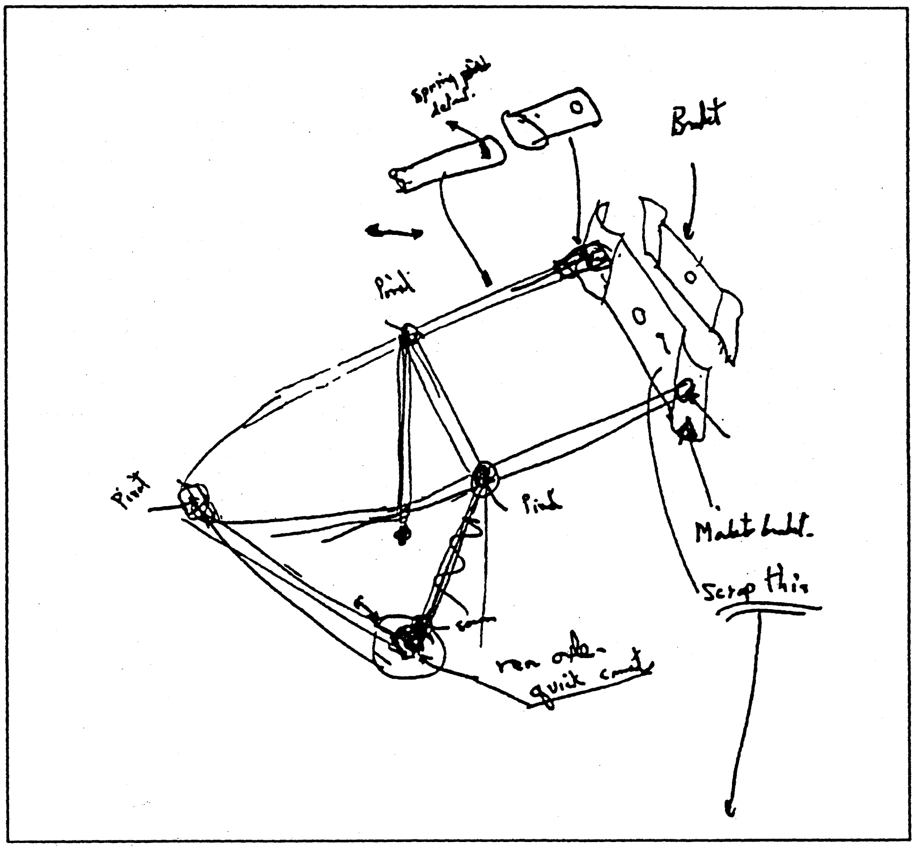

Figure 2: Dan's detailed development of his design.

In the meanwhile, as we noted above, Dan also used the client's requirement of a unique selling proposition to help guide and to reinforce his decision to seek a design based on triangular structures:

> (01.10)
> that is going to be our proprietary feature, a triangular, rigid structure with no bends in it; these rods are then going to be in tension and compression, no bending
>
> (01.41)
> I want to make sure that this rod here comes to a point, not stop right there . . that's to a point; that's going to be my feature

In these comments, Dan demonstrated that he regarded the pronounced triangular form at the rear of the product as something to be maintained as a feature that would help give the product an attractive, unique selling point.

3.5 Summary of Dan's Design Approach

Dan's design for the carrying device is an integrated design in which user requirements are addressed through the problem frame of stability, leading to the use of triangularity as the guiding first principle, which also addresses the client's goal of having a proprietary, unique selling feature to the product, as summarised in Figure 3.

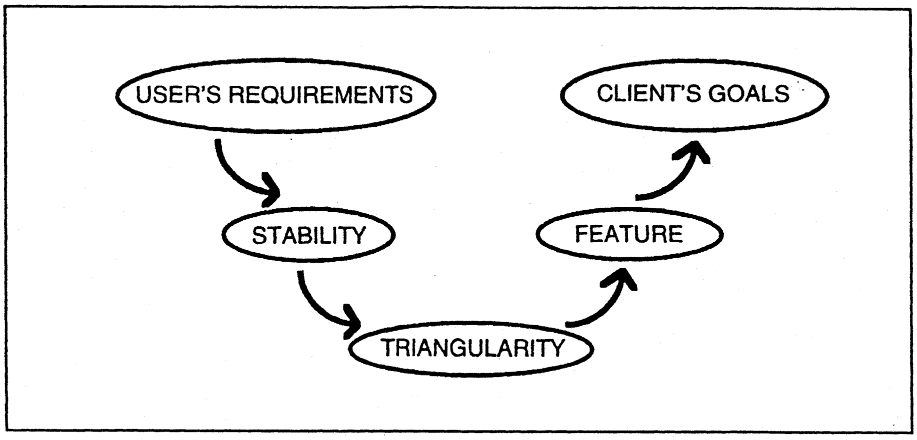

Figure 3: Dan's approach summarised as hierarchical levels of systemic design, problem framing and designing from first principles.

4. Discussion: Expertise in Design

We believe that we have been able to demonstrate that there are similar aspects in the design approaches of two outstanding expert designers. Both take a systemic approach to the overall design task; both frame the design problem in a way that challenges them to innovate; and both use first principles to guide their conceptual and detail designing. It is perhaps surprising that we see commonalities between these two designers, considering the great disparity between the design projects in which they were engaged – between Formula One racing cars and a simple bicycle luggage rack!

Therefore it seems that some common aspects of expertise are shared by these two outstanding designers. Outstanding designers may not have developed, or been gifted with, particular, unique strategies and approaches to design, but may be using similar strategies and approaches as other designers. In that case, we may hope that these successful strategies and approaches not only can be identified in outstanding designers but also can be coached and developed in less expert and novice designers.

Expertise has been studied in other fields (see, for example, Ericsson and Smith [4]), but so far there are few studies of expertise in design. What we can learn from these studies in other fields is also limited, because of the particular, distinctive characteristics of design activity. Many of the classic studies of expertise have been based on examples of game-playing (e.g. chess), or on comparisons of experts versus novices in solving routine problems (e.g. physics). These are all well-defined problems, whereas designers characteristically deal with ill-defined problems.

However, some studies of expertise in fields such as creative writing and computer programming, where problems are more ill-defined, do suggest some parallels with our observations of expert designers. Holyoak [5] has reviewed studies which suggest that some of the 'standard' results from studies of expertise do not match with results from studies of expertise in creative domains. For example, creative experts will define the given task so that it is problematic – i.e. deliberately treat it as ill-defined – which is contrary to the assumption that experts will generally solve a problem in the 'easiest' way, or certainly with more ease than novices. In some ways, therefore, creative experts treat problems as 'harder' problems than novices do. We have seen that both Gordon and Dan are not content to adopt an 'easy' view of the design problem that they are given; both of them choose to take harder, more innovative routes to finding a solution concept. In Gordon's case, it seems clear that deliberately challenging the given design 'rules', such as the technical constraints set by the governing body of his sport, has been a feature of his successful design approach.

Experts in creative fields are also reported to devote considerable time to constructing a problem representation, exploring constraints, etc. Again, we have seen this with both Gordon and Dan. In Dan's case, we saw that he devoted a major amount of his available time to reaching an understanding of the problem, and the potential solution space, before beginning to create a concept within the appropriate segment of that solution space. Gordon will allow himself 'incubation' time, which helps him to reach a new, creative insight.

In comparisons of experts and novices, experts are reported to make a breadth-first search for a global solution concept, whereas novices in the field will often get lost in depth-first searches in more detail. Creative experts are also reported as solving similar tasks from first principles each time, rather than recalling previous solutions. In these instances again, we see similarities with our observations of expertise in design, in our studies of Gordon and Dan. Neither of them gets lost in details, but always seems to have an overall, global concept that guides detail decisions. This is the importance of the 'problem frame' that they adopt. They also both have an approach in which experience of previous solutions is 'at the back of the mind, not at the front', as Gordon expressed it, and both refer, either directly or indirectly, to 'first principles' as the stimuli for creative design.

5. Conclusions

We have been able to explore the strategies employed by two outstanding expert designers, and have found some parallels in their ways of working. In order to create innovative designs, they adopt a systemic view of the design situation, frame their view of the problem in a challenging way, and then use 'first principles' of engineering to guide the generation of the design concept and its detailed development.

Our observations also tend to fit with other findings about the cognitive strategies employed by experts working in other creative domains where problems are ill-defined. It is important to recognise the distinctions between strategies employed by creative experts and those employed by experts working in well-defined problem domains and in routine problem solving. Any general theories of expertise, and any applications in education and practice drawn from more general studies of expertise, need to recognise these distinctions between expertise in creative and routine problem solving.

It is important that we learn more about expertise in design. Too many studies have been based on novices or, at best, mediocre designers. Studying novice and average designers may well limit our understanding of design, holding back progress in design methodology and leading to weak or even inappropriate models of design activity. Studying expert designers might enable us to identify the seeds of 'best practice', and then to transfer these insights more widely across the professions. This should also be useful in education, for guiding the development of better-than-average designers.

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