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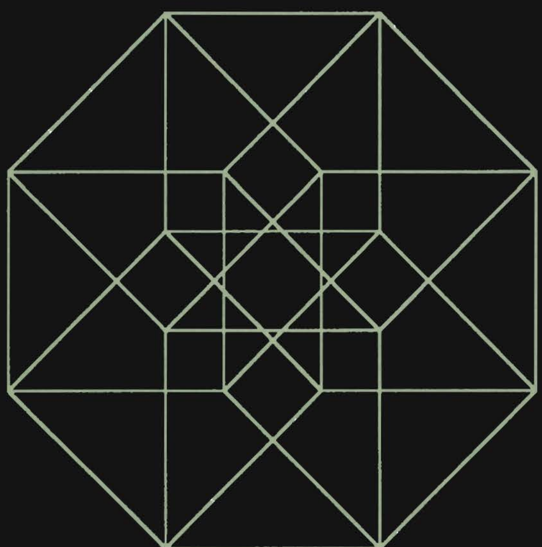

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Design of Industrial Systems

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Summary

Industrial systems designers are involved in the design of *products* and the *production system* that is able to produce these products. Primary attention is paid to the object to be designed, being the products on the one hand and production system on the other. The object to be realised (the *object design*) is designed in a *design process*, the process of decision-making on the object design. This decision-making can be modelled as the four-step decision cycle: (1) *analysis*, (2) *synthesis*, (3) *evaluation*, and (4) *decision*. This decision-making process can be designed or structured. It is claimed that designing the design process has a positive effect on the object design: better products and production systems will result, because structured design will pay requisite attention to the strategic design problems.

A design process can be seen as moving from the upper plane in a *design cube* to the lower plane. The three axes of the design cube are the *sub-systems* the object consists of, the *attributes* describing the various sub-systems and the level of *design abstraction* describing the degree of detail in the object design. Structuring of the design process can be done by dividing the design cube in a proper and sensible way. A five-step procedure can be followed to structure an individual design process: (1) the formalisation of the objective definition, (2) the division of the object to be designed into basic sub-systems, (3) phasing of the design processes of the various basic sub-systems, (4) identification of the relevant attributes for every design phase, and (5) selection or development of supporting methods for all four steps of the decision cycle (analysis, synthesis, evaluation and decision).

The feasibility and usefulness of structured design are often denied. The structuring of design processes should, therefore, be carried out by carefully investigating the design problem as well as the designer. The structuring of design processes can help the designer to guide his decision-making. Important and strategic design decisions receive requisite attention. The often observed tendency of designers to rush through the abstract phases of design and to pay much attention to the concrete and detailed phases can thus be avoided. Another important advantage of structured design is the fact that the designer will make the *conceptual model* on the object design he has in his mind explicit in prescribed *design documents*. Evaluation possibilities are increased, because communication with other experts is improved and evaluation techniques that are more formal than mental simulation can be deployed.

The concepts that have defined and discussed have been used to structure the industrial system design process. The five steps that have been identified in the structuring of design processes have been carried out consecutively. The first step involves the formalisation of the objective definition. The three steps that have been prescribed for objective definition have been made concrete for industrial systems. The first step of the objective definition involves the identification of the Interested External Systems (IES's). Seven IES's have been identified: (1) *matter suppliers*, (2) *matter consumers (customers)*, (3) *financiers*, (4) *equipment suppliers*, (5) *equipment consumers*, (6) *labour market*, and (7) *government*. The *hard constraints* these systems place on the industrial system to be designed are identified in the second step of objective definition. By doing so, all valid object designs can be identified; the best object design, however, cannot be termed. The *soft constraints* are identified and weighed in the third step of objective definition such that comparison of valid object designs is possible and the best object design can be selected.

The second step in the structuring of the industrial system design process consists of the identification of basic sub-systems. An industrial system consists of a set of products and a production system that is able to produce those products. The production system consists of a *manufacturing system*, that is responsible for the flow of material in the industrial system, an *information system*, that is responsible for the information flow, and a *financial system*, that is responsible for the flow of money. The information system, in turn, consists of a *(matter) control system*, controlling the manufacturing system and a *financial control system*, controlling the financial system.

The third step in the structuring of the industrial system design process consists of the phasing of the design processes of the various basic sub-systems. The product design process has been divided into three phases: *function-definition* phase, *working-principle-definition* phase and the *form-definition* phase. The design processes of the sub-systems of the production system have all been phased identically: the design process starts with the *processes* phase, continues with the *processors* phase and ends with the *means* phase. Design documents have been defined and discussed for the product, manufacturing system and control system design processes.

The fourth step in structuring the industrial system design process involves the identification of the attributes that are most relevant in the various design phases that have been defined earlier. This has been carried out for the various basic sub-systems, with

special attention the product, the manufacturing system and the control system. Together with the identification of the relevant attributes, methods and techniques have been discussed to support decision-making in the various design phases. Methods and techniques to support analysis, synthesis, evaluation as well as decision have been discussed. The execution of the five steps has resulted in a general structured design method for the design of industrial systems. The standard structure can be adapted to the individual needs by the application of the theoretical concepts.

The claimed positive effects of structured design have been tested empirically. Sixteen designers were divided into two groups of eight designers each. The first group was made familiar with the structured design of industrial system, whereas the second group received a refresher course in a conventional design approach. The first hypothesis, that stated that better object designs would result using structured design, could not be supported by the test results. Too many other effects played an important role. The second hypothesis, that stated that the designers using structured design would address more abstract design problems, was supported by the test results. The designers in the structured design group, for example, spent seven times more time on process selection than did the test group. More empirical research is necessary to prove the claimed positive and negative effects of structured design.

In addition to this, structured design has been applied in a realistic industrial case. The history of the design process of a rubber-processing industrial system has been investigated and compared with structured design. The influence of a dynamic environment on the performance of the industrial system has become clear. It showed that much attention has been paid to the more concrete design problems. The relations between the design of the products, the manufacturing system and the control system have caused major iterations. The application of structured design would possibly have avoided these major iterations. The application of structured design in other industrial cases has shown that the designer and his client are positively guided in their decision-making. Therefore, it can be stated that structured design is beneficial for both the quality of the design process as well as the quality of the object design.

Samenvatting

Ontwerpers van industriële systemen hebben te maken met *produkten* en een *produktiesysteem* dat deze produkten kan produceren. Hun voornaamste aandacht gaat uit naar het object dat dient te worden ontworpen: het *objectontwerp*. Dit betreft in het onderhavige geval enerzijds het produktontwerp en anderzijds het produktiesysteem-ontwerp. Dit objectontwerp ontstaat in een *ontwerpproces*: het proces van het nemen van ontwerpbeslissingen over het te ontwerpen object. Dit nemen van ontwerpbeslissingen kan worden gemodelleerd als een cyclus van vier stappen: (1) *analyse*, (2) *synthese*, (3) *evaluatie* en (4) *beslissing*. Dit beslissingsproces op zijn beurt kan worden ontworpen oftewel gestructureerd. Er wordt gesteld dat het ontwerpen van het ontwerpproces een positieve invloed heeft op het objectontwerp: betere produkten en produktiesystemen zullen worden ontworpen, omdat de ontwerper de nodige aandacht zal besteden aan de meest relevant ontwerpproblemen, indien hij gebruik maakt van gestructureerd ontwerpen.

Een ontwerpproces kan worden gezien als het komen van het bovenste vlak van een *ontwerpkubus* naar het onderste vlak. De drie assen van de ontwerpkubus zijn achtereenvolgens de *subsystemen* waaruit het object bestaat, de *attributen* die de verschillende subsystemen beschrijven en tenslotte het niveau van *ontwerpabstractie* dat beschrijft tot op welk detailniveau het objectontwerp bekend is. Het structureren van een ontwerpproces kan nu worden gezien als het kiezen van een verstandige verdeling van deze ontwerpkubus. De procedure voor het structureren van ontwerpprocessen bestaat uit vijf stappen : (1) het formaliseren van de doeldefinitie, (2) de verdeling van het te ontwerpen object in hoofd-subsystemen, (3) het faseren van de ontwerpprocessen van de hoofd-subsystemen, (4) de identificatie van de relevante attributen in elke gedefinieerde ontwerpfase, en (5) de selectie en eventueel ontwikkeling van ondersteunende methoden en technieken voor alle vier de stappen in de beslissingscyclus (analyse, synthese, evaluatie en beslissing).

De mogelijkheid en het nut van gestructureerd ontwerpen is een veel bediscussieerd onderwerp. Het structureren van ontwerpprocessen dient daarom aandacht te besteden aan het onderhavige ontwerpprobleem en de betreffende ontwerper. Het structureren van ontwerpprocessen kan een ontwerper sturen tijdens het nemen van ontwerpbeslissingen. Daarbij krijgen belangrijke, strategische ontwerpbeslissingen de nodige aandacht. Het vaak geobserveerde gedrag van ontwerpers die weinig tijd besteden aan de abstracte

ontwerpfasen en des te meer tijd besteden aan de concrete fasen, kan op deze manier worden voorkomen. Een ander belangrijk voordeel van gestructureerd ontwerpen is het feit dat een ontwerper gedwongen wordt het *conceptuele model* van het objectontwerp dat alleen in zijn gedachten bestaat, expliciet te maken in de vorm van tevoren gedefinieerde *ontwerpdocumenten*. Evaluatie van het objectontwerp wordt op deze manier verbeterd, niet alleen doordat er met andere experts kan worden gecommuniceerd, maar ook doordat evaluatie technieken kunnen worden toegepast die formeler zijn dan mentale simulatie.

De gedefinieerde en behandelde concepten zijn gebruikt voor het structureren van ontwerpprocessen van industriële systemen. De hierboven genoemde vijf stappen voor het structureren van ontwerpprocessen zijn daartoe toegepast op industriële systemen. De eerste stap betreft het formaliseren van de doeldefinitie. In het theoretische deel zijn daarvoor drie stappen voorgeschreven: de eerste stap van de doeldefinitie dient ter identificatie van de Belanghebbende Systemen. Zeven Belanghebbende Systemen zijn geïdentificeerd voor industriële systemen: (1) *materiaal toeleveranciers*, (2) *materiaal afnemers (klanten)*, (3) *financiers*, (4) *equipment leveranciers*, (5) *equipment afnemers*, (6) *arbeidsmarkt* en (7) de *overheid*. De *eisen (hard constraints)* die deze systemen stellen aan het te ontwerpen systeem worden in de tweede stap geïdentificeerd. Na deze stap kunnen alle valide objectontwerpen worden bepaald, maar kan nog niet worden bepaald welk objectontwerp het beste presteert. Daartoe worden in de derde stap de *wensen* (*soft constraints*) geïdentificeerd en gewogen.

De tweede stap in het structureren van het ontwerpproces van industriële systemen betreft het identificeren van de hoofd-subsystemen. Een industrieel systeem bestaat uit een verzameling produkten en produktiesysteem dat deze produkten kan voorbrengen. Het produktiesysteem bestaat uit een *fabricagesysteem*, dat gerelateerd is aan de materiaalstromen door het industriële systeem, een *informatiesysteem*, dat gerelateerd is aan de informatiestromen en een *financieel systeem*, dat gerelateerd is aan de geldstromen. Het informatiesysteem op zijn beurt bestaat uit een *(materiaal) besturingssysteem*, dat het fabricagesysteem bestuurt, en een *financieel besturingssysteem*, dat het financiële systeem bestuurt.

De derde stap in het structureren van het ontwerpproces van industriële systemen betreft het faseren van de ontwerprocessen van de verschillende hoofd-subsystemen. Het produkt ontwerpproces is verdeeld in drie fasen: (1) de *functie bepalende* fase, (2) de *werkwijze bepalende* fase en (3) de *uitvoeringsvorm bepalende* fase. De ontwerpprocessen van de subsystemen van he produktiesysteem zijn alle op gelijke wijze gefaseerd: het ontwerpproces start met een fase waarin de *processen* worden vastgelegd, vervolgens worden in de tweede fase de *processoren* gedefinieerd en tenslotte worden de *middelen* ontworpen. Ontwerpdocumenten zijn voorgesteld en behandeld voor de ontwerpprocessen van de produkten, het fabricagesysteem en het besturingssysteem.

In de vierde stap van het structureren van het ontwerpproces van industriële systemen worden de diverse attributen geïdentificeerd die relevant zijn in de verschillende gedefinieerde ontwerpfasen. Dit is uitgevoerd voor de verschillende hoofd-subsystemen, waarbij de voornaamste aandacht is uitgegaan naar de produkten, het fabricagesysteem en het besturingssysteem. Na de identificatie van de relevante attributen, zijn in de vijfde stap een aantal ondersteunde methoden en technieken behandeld. Deze methoden en technieken ondersteunen zowel analyse, synthese, evaluatie als beslissing.

De vermeende positieve effecten van gestructureerd ontwerpen zijn empirisch getest. Zestien ontwerpers zijn hiertoe in twee groepen verdeeld van elk acht ontwerpers. De eerste groep is middels een college bekend gemaakt met gestructureerd ontwerpen, terwijl voor de tweede groep een college over een conventionele benadering is gegeven. De eerste hypothese, die stelde dat de ontwerpers die gestructureerd ontwierpen betere objectontwerpen zouden produceren, kon niet worden bevestigd door de testgegevens. Te veel andere factoren lijken hier een rol te hebben gespeeld om hierover positieve uitspraken te kunnen doen. De tweede hypothese, die stelde dat de ontwerpers die gestructureerd te werk zijn gegaan meer abstracte ontwerpproblemen zouden bestuderen, kon door de testgegevens worden bevestigd. De ontwerpers die gestructureerd hebben ontworpen hebben bijvoorbeeld zeven keer zoveel tijd gespendeerd aan proceskeuze dan de ontwerpers in de controlegroep. Meer empirisch onderzoek is nodig om de vermeende positieve alsook de negatieve effecten van gestructureerd ontwerpen te onderzoeken.

Daarnaast is gestructureerd ontwerpen gebruikt om de geschiedenis van het ontwerpproces van een rubber-verwerkende industrie in kaart te brengen. Op deze manier is het mogelijk gebleken gestructureerd ontwerpen te vergelijken met een intuïtieve benadering van het ontwerpproces. Het is gebleken dat in het ontwerpproces relatief veel aandacht is besteed aan detailvraagstukken. De relatie tussen het ontwerp van de produkten, het fabricagesysteem en het besturingssysteem heeft daarbij grote iteraties nodig gemaakt. Mogelijkerwijs had een meer gestructureerde benadering deze grote iteraties voorkomen. Daarnaast is de invloed van een dynamische omgeving op de prestatie van een industrieel systeem duidelijk aan het licht gekomen.De toepassing van gestructureerd ontwerpen in andere industriële cases heeft aangetoond dat de ontwerper en zijn opdrachtgever in hun ontwerpbeslissingen positief worden gestuurd. Daarom is het gerechtvaardigd te stellen dat gestructureerd ontwerpen een positieve bijdrage levert aan de kwaliteit van zowel het ontwerpproces als het objectontwerp.

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Chapter 1

Introduction

'Impossible. The industrial system design process is too complicated to be formalised. Therefore, no industrial system design method is possible.' This belief is expressed by many industrial system designers and researchers.
An industrial system can be defined as consisting of products and a production system producing the products, and design can be defined as decision-making concerning some object to be realised. The industrial system design process, therefore, involves decision making concerning products and the production system. 'Too many aspects play a relevant role'. 'Every design process needs an individual approach'. 'Only the creativity and intuition of the experienced designer can, therefore, be a safeguard for a satisfying design'. The industrial system design process is perceived to be too complex to be formalised.

Yet, decision-making can be supported by the deployment of various methods and techniques. Design methods for the optimisation of certain aspects of product design have been developed. Various handbooks discuss the product design process, for example [Pahl, Beitz, 1984; Roozenburg, Eekels, 1991; Cross, 1991; Ullman, 1992]. Numerous methods and techniques are discussed in these books that can be used to support intuitive decision-making. Chapter 2 will discuss more examples of supporting methods and techniques for the product design process. In spite of these methods, product design is still largely an intuitive process.

Recently, the relation between products and the production system has received more attention. Methods and techniques have been developed for so-called Design for Manufacturing or Concurrent Engineering [Sohlenius, 1992]. These methods take the production system into account while optimising product design [Bralla, 1986; Bakerjian, 1992]. Design for Assembly [Boothroyd, Dewhurst, 1983] is an example of a Design for Manufacturing method: product design is optimised concerning its assembly. Spectacular results have been achieved by the deployment of Design for Assembly and other Design for Manufacturing methods [Bedworth et al., 1991]. Chapter 2 will discuss more methods and techniques that fall in the category of Design for Manufacturing.

Furthermore, design methods have been developed that can be used to support decision-making in production system design. Methods have been developed that can be used for production system design. Group technology [Burbidge, 1971] and Sociotechnics [De Sitter, 1986] are production system design methods that can be applied in some specific cases. General approaches to production system (re-) design, like Just-in-Time [Shingo, 1981; Schönberger, 1982] and OPT [Goldratt, Cox, 1992; Goldratt, Fox, 1986] have also proved to be applicable in only few cases. Another general approach, Lean Production [Womack et al., 1991], has general value, but it only presents some guidelines for production without waste. Many other design methods have been formulated. Wu [1992] formulated a production system design method based on system theory. Black [1991] has proposed a production system design method based on Axiomatic Design [Suh, 1991]. Mintzberg [1979] has formulated ideas for the structuring of organisations. Other production system design methods focus on a small, apparently important, part of production. Shingo [1985], for instance, has formulated the SMED method: a method for the reduction of set-up times. Currently, no truly integral production system design method exists that is applicable for all possible production systems. Chapter 2 will discuss more examples of production system design methods.

Much knowledge has been formalised in numerous design methods. This knowledge can productively be used in an industrial system design process. The use of these methods, however, is hindered by the fact that no structure exists in which to use the methods. The use of a structured design process can help the designer to structure his thoughts. It should point out which aspect to study at which moment and, consequently, which design method to deploy when. The design process then becomes a structured design process in which decision-making is guided and supported where possible.

In addition to many design methods and techniques, various modelling techniques have also been developed. Whereas design methods support decision-making in a direct way, modelling techniques can support decision-making by the improvement of evaluation possibilities. Designers can, for instance, communicate more easily on their designs. The introduction of the computer has improved evaluation possibilities even further. Formal evaluation has become possible. Models of the object to be realised can be made in the design process. Mathematical techniques enable the evaluation of these models. The deployment of modelling and evaluation techniques can avoid expensive redesign projects, because deficiencies in the design are discovered before implementation.

The introduction of Computer Aided Design and Computer Aided Engineering in product design has improved communication and evaluation possibilities. Besides this, the design process will evolve more quickly, because, for instance, part of previous designs can be used again. The introduction of modelling and simulation techniques has improved the quality of the production system design process. The performance of the production system can be tested and optimised before implementation. Chapter 2 will discuss more examples of product and production system modelling techniques.
The deployment of modelling techniques, however, also needs structuring. Communication and evaluation can further be improved by the structured use of modelling techniques. This structure should point out where and when to use which modelling technique.

In summary, the industrial system design process is currently an intuitive decision-making process. The designer's attention is directed almost exclusively towards the *object design*. This intuitive decision-making is sometimes supported by more formal methods and techniques. Both design methods and modelling techniques can be applied. Decision-making can be structured by pointing out where and when to use which method. In other words, not only the object needs to be designed, but also the *design process* needs to be designed.
This implies that the industrial system design process needs to be designed (or structured). The deployment of the design methods and techniques as well as the modelling techniques should be structured to further improve the quality of the design process and the object to be designed.

The design processes of the product and the production system should not be structured separately. A method for the structured design of industrial systems should pay attention to the integrated design of products and the production system. By doing so, the ideas behind Concurrent Engineering are applied. The application of structured design will force the product designer to consider the consequences of his decisions for the production system.

On the other hand, the production system designer is forced to pay attention to the needs of the product designer. By doing so, an optimal industrial system can be attained.

The possibility of structuring the industrial system design process, however, is questionable. Many designers and researchers have expressed doubts. The objectives of the research presented in this dissertation, therefore, are as following. The first research objective is to develop concepts for the designing (or structuring) of design processes. The concepts developed in this research will have to be such that the designer will 'automatically' address important strategic design decisions. The second research objective is to use the earlier defined concepts to develop a structured industrial system design process. The third research objective is to prove the claimed benefit of the deployment of structured design.
This dissertation describes the development and deployment of structured industrial system design. A standard structure of the industrial system design process can be formulated. The uniqueness of an industrial system design process, however, requires the deployment of a tailor-made structure. A standard, but flexible structure is, therefore, required.

To achieve the objectives that have been stated for this research, several research steps are required. Firstly, theory on the structuring of design processes needs to be developed. Different design strategies need to be incorporated in this design methodology. The concepts defined in this research can be used by the designer to design the design process of the object he wants to design. This general theory then needs to be applied for the structuring of the industrial system design process. A structured design method will result and the second research objective will have been achieved. The general concepts can be used to adapt the standard structure to the individual needs. To achieve the third research objective, the structured design method needs to be tested and compared with unstructured design. The structured design method can be tested empirically and applied in realistic situations. Comparison will then be possible.

This dissertation, therefore, is organised as following. A review of design research is given in Chapter 2. Attention is given to the modelling of the design process as well as to the modelling of the designed object. Product and production system modelling are treated. Each of the aspects is discussed concerning its history and its state of the art. This Chapter will discuss the need for a structured design process in more detail. Therefore, in Chapter 3, the structuring of design processes is discussed. The theory developed in this Chapter can be applied to all design processes. Chapter 3, therefore, is a contribution to design methodology. The application of this theory in the structuring of the industrial system design process is treated in Chapter 4. There, a standard structure for the industrial system design process will be proposed. This structure has been tested empirically. A small empirical test and its results are described in Chapter 5. The use of intuitive design is compared with structured design in Chapter 6. For this, the design process of a particular industrial system is traced in different time periods, showing the benefits of structured design. The dissertation will be completed with conclusions in Chapter 7 and suggestions for future research in Chapter 8.

Chapter 2

Design Research

Industrial systems are often designed using an intuitive approach. The products, manufacturing system, control system and other sub-systems of the industrial system are not designed in a structured way. The designer uses his experience to formulate good solutions to the problems he comes across. No systematic approach is used. A 'good' designer will make better decisions than a 'bad' designer. Equally, an experienced designer will make better decisions than a novice designer. If the designer's knowledge on the subject is outdated or incorrect, bad designs can easily result. Since his own knowledge is the only hold the designer has, the quality of the designs depends entirely on the quality of the designer. This situation needs improving.

The need for a more systematic approach to the design process has been discussed in the first Chapter. Developments in design theory can help in achieving the objective of a more systematic approach. Recently, design research has revealed many useful approaches and design methods. Therefore, design research will be discussed in this Chapter. No detailed survey of all possible approaches, design theories and methods will be given. An outline of current design research will be presented.

Many publications surveying this topic can be found. Finger and Dixon published a series of articles on the current state of design research [1989a; 1989b]. Ullman discusses the product design process in his book [1992]. Cross also discusses the product design process [1991]. Other publications come from Eekels and Roozenburg [1991], dealing with the product design process; Nevill [1989] and Bell, Taylor and Hauck [1991], dealing with computable design process models. A survey of current design research can be found in the proceedings of the International Conferences on Engineering Design

(ICED) (for example [Hubka, 1991; Roozenburg, 1993]) and the proceedings of the conferences on Design Theory and Methodology (for example [Rinderle, 1990]).

Firstly, some definitions will be given that will be used throughout the dissertation. These definitions include object design and design process models. Secondly, models of object designs will be briefly discussed. After reviewing their history, some examples of object design models will be given. Thirdly, models of the design process will be discussed. After a historic survey, the phasing of the design process will be discussed. Next, detailed and general design methods will be treated. Detailed design methods can only be used in a specific area, whereas general design methods can be used throughout the design process. Cognitive design research will then briefly be discussed. Finally, the Chapter will be concluded with a review on recent developments in design theory.

The research presented in the next Chapters will be based on the design theory review presented in this Chapter. The structuring of the design process will be discussed in Chapter 3. Following, the structuring of the industrial system design process will be discussed in Chapter 4.

2.1. Definitions

Here, an industrial system is seen as the collection of products and a production system. In this way, the design of an industrial system involves the design of both products and the production system. Seeing both products and production system as part of an industrial system, emphasises their close interrelationship. The design, therefore, of an industrial system will naturally follow the ideas of Concurrent Engineering. By doing so, a design decision concerning the product will not be made without proper consideration of its consequences for the production system.

Firstly, some definitions will be given using the phases in the life of a production system. Five phases can be distinguished. These are the orientation phase, the specification phase, the realisation phase, the utilisation phase and the elimination phase [Rooda, 1991a]. Figure 2.1 shows the five phases in the life of a production system. Its life begins with nothing and, optimally, ends with nothing. In the orientation phase, the objective of the production system is defined. After this, the production system is designed in the

specification phase. This results in an abstract system. An abstract system is a model, an abstraction of a concrete system. In the realisation phase, the production system is made according to this specification. This results in a concrete system. A concrete system is a system that exists in three-dimensional reality. The production system is used in the utilisation phase. After the production system has been used for a while, the system no longer performs according to its objectives. The production system has become obsolete and the obsolete production system is eliminated in the elimination phase.
This dissertation shall consider the first two phases. The design of the third phase, the realisation phase is not treated in this dissertation. The design of the realisation phase involves the planning of the implementation of the newly designed or redesigned production system.

nothing
Orientation phase
objective
Specification phase
abstract system
Realisation phase
concrete system
Utilisation phase
obsolete system
Elimination phase
nothing

Figure 2.1. Five phases in the life of a production system [Rooda, 1991a].

The lifes of products consist of five similar phases, starting with the definition of the objective in the orientation phase. The product is designed in the specification phase and it is realised in the realisation phase during the utilisation phase of the production system. Next, the product is used in the utilisation phase and, finally, the product is eliminated in the elimination phase after it has become obsolete. The product realisation phase coincides with the production system utilisation phase. The relation between product and production system design will be discussed in Chapter 4.

Next, some definitions concerning design will be given. The use of the word 'design' can lead to confusion as to whether the noun or the verb is intended. To avoid this confusion, some discriminating terms will be introduced. The term 'object design' will be used to designate the noun. An object design is a *conceptual model* of the object to be realised. This conceptual model only exists in the mind of the designer. A model can be made of this conceptual model. Communication on the object design then becomes possible. A drawing, a sketch and a computer model all are models of object designs at different levels of abstraction. The term 'design process' will be used to refer to the decision-making process. The verb design is reserved for the activity of making design decisions. A design decision is a decision that makes the object design more concrete.

The design of an industrial system begins with nothing and ends with a specification of that system. In the beginning of the design process, knowledge on the object to be designed is abstract[1]. The conceptual design – the object design – is abstract. This knowledge becomes more concrete during the design process. The object design has become concrete at the end of the design process. The conceptual model or the object design – in other words, the knowledge – goes from abstract to concrete.

Distinct from the level of *design abstraction* is the level of *modelling abstraction*. Abstract models can be made of concrete systems. Knowledge is abstracted, meaning that less knowledge is represented in a model than is available. Consequently, abstract models can both be made of abstract as well as concrete object designs. A model of an abstract object design will model much of the knowledge in the object design: not much modelling abstraction is done. An abstract model of a concrete object design will model little of the knowledge in the object design: much modelling abstraction is done. The term 'modelling abstraction' will be used in contrast to the term 'design abstraction'. The word 'abstraction' is used where no ambiguity is possible.

Finally, the relationship between design and redesign will briefly be discussed. Redesign can be seen as an iteration on the previous design process. This iteration may have become necessary because of changes in the environment of the designed object. Redesign can also be necessary if the object performs unsatisfactory. Iteration, and redesign, will be discussed in Chapter 3 in more detail.

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[1]Knowledge is always abstract. An object design is always an abstract system, see figure 2.1. The term 'abstract knowledge' is intended as an abbreviation of knowledge referring to an object of which little is known. The term 'concrete knowledge' is intended as an abbreviation of knowledge referring to an object of which much is known.

Following, the modelling of object designs will be discussed. After a short historical review, some examples of object design models will be given. After this, the modelling of the design process will be treated.

2.2. Modelling of the Object Design

Ever since the invention of the celt, man has designed and made things. In the stone-age, no models of the object design were made. The ideas on the object to be made existed only in the caveman's mind. Only the conceptual model existed and no sketches were made. Each time a celt was to be made, an appropriate stone had to be sought and adapted to the individual hunter's or butcher's needs. Knowledge on celts could only be found in prehistoric brains; only conceptual models were made, but no representation was made whatsoever. Communication, therefore, was oral. The Caveman's Design Approach still lives on in many engineering disciplines.

The disadvantages are apparent. The design of more complex apparatuses especially requires some more formal communication protocol. The ancient Egyptian master builders, therefore, used sketches on papyrus and clay to draw their object designs. This alone made possible such geometric precision in their buildings. Mentoehotep's communication protocol has survived until the present day.

Heron of Alexandria, who lived in the first century B.C., used sketches as a model of his stunning apparatus: moving temple doors and holy water automatons. Leonardo da Vinci (1452 - 1519) also used sketches to design his parachute, moving bridge and spring driven cart. Today, the sketch is the main means of communication in abstract phases of car design. Only recently, other forms than the sketch have entered the design community.

With the growth of scientific knowledge in physics, chemistry and mathematics, more formal models of the object design became possible. With these new models it became possible, not only to sketch a future object, but also to make an electrical scheme, to set up a differential equation of its behaviour in time, etc. Whereas the sketch was primarily used as a communication means and a mnemonic, models of the object design could now also be used for formal evaluation purposes.

So far, evaluation had to take place using so-called *mental simulation*. The designer (or a future user) imagines the behaviour of the object design. The behaviour, in other words, is mentally simulated. Mental simulation, therefore, is subjective and likely to be inaccurate. A more formal means of evaluation would improve the quality of both the design process and the object design.

With the introduction of formal modelling techniques, the behaviour could be calculated. Now, an important new fact was introduced into design. The object design could be evaluated in a more formal and precise way. So far, evaluation was always subjective and inaccurate. Expensive iteration could now better be avoided, making more complex object designs possible. The design of modern integrated circuits would be impossible without the use of formal models of the object design.

Engineering practice has profited only recently from these scientific successes. Until this century, many engineering problems were too difficult to solve. All modelling and evaluation took place in the designer's mind. His sketches were his only support. The use of formal representations has helped designers to cope with complexity.

Next, representative examples of object design models will be discussed. Two categories will be distinguished. Firstly, product models will be discussed. Secondly, models of production systems will be treated.

2.2.1. Product Modelling

The modelling of products will be discussed in this Section. No full list of all possible representations will be given. An outline of some widespread modelling techniques will be given. Most simple modelling techniques as well as highly sophisticated techniques are treated. Three classes of product models will be discussed: iconic models, symbolic models and scale models.

An iconic modelling technique only uses a two-dimensional representation: icons and graphical symbols. The most simple iconic technique to model a product object design is sketching. The sketch can be used in all phases of the design process, i.e. all levels of design abstraction can be represented. The level of modelling abstraction, however, is high when modelling concrete object designs. Rough sketches of alternative concepts can be sketched as well as detailed versions of the concrete object design. The sketch is often used in areas where no other representation technique is available, where modelling needs to be quick or where aesthetics plays an important role.

A more formal way of representation is the (technical) drawing. National and international standards have been adopted. Technical drawings in the Netherlands are made using the NEN-norms [NNI, 1983]. German DIN-norms and international ISO-norms are also developed for unambiguous drawing. Whereas the sketch is an impression of the object design, the technical drawing is precise. The sketch, therefore, has a higher level of modelling abstraction than the technical drawing. An electrical scheme is also a kind of (technical) drawing. Electrical schemes can be made to model an (electrical) part of an object design. Schemes or diagrams are also used to model mechanisms, for example.

Sketches, drawings, schemes and diagrams can be classified as iconic models of the object design. Iconic models are used for communication purposes and as a mnemonic. Evaluation takes place using mental simulation. More formal iconic models can be a help for more formal evaluation. The electrical scheme, for instance, is the input for the evaluation using (electromechanical) formulas. The iconic model itself, however, cannot be evaluated. For this, a translation into a symbolic model is necessary.

Modern versions of iconic modelling techniques make use of a computer. The techniques that fall into this category are categorised as Computer Aided Design-techniques (CAD). CAD, however, is a diverse field. The part of CAD that produces iconic models is called Computer Aided Drafting (CADR). The result of CADR is an iconic model of the object design. CADR-techniques are computerised versions of the drawing table. The designer is supported in his drawing activities, resulting in a quicker design process, because less time is spent in drawing. The early versions of CADR used wire-frames to model the object design. Wire-frame modelling was followed by solid modelling. Later, the use of pre-defined features further increased the speed of the product design process [Longenecker, Fitzhorn, 1989; Stiny, 1991].

In producing iconic models, mental simulation is the only direct evaluation possibility for CADR. The advantages of computerised drafting, therefore, are to be found in quick and accurate modelling. Evaluation, however, is not formalised. Therefore, more formal models of object designs are required. Models that can be formally evaluated are classified as symbolic models [Rooda, 1991b]. Symbolic modelling techniques use mathematical, symbolic, expressions. Whereas iconic models are mainly used for communication, symbolic models are better suited to evaluation. Symbolic models, however, often are less suitable for communication purposes.

A product object design, in other words, can be modelled as a set of mathematical expressions. These mathematical expressions can be differential equations, modelling for instance mass balances, or the course of temperature. The behaviour of the object design can be evaluated by solving these mathematical expressions. Generally, only a few attributes of the product are modelled.

Modern versions of symbolic modelling technique make use of a computer. This part of CAD is called Computer Aided Engineering (CAE).
An example of a CAE-technique is the Finite Element Method (FEM) [Zienkiewicz, Taylor, 1989]. The product is modelled using a set of elements with known kinematic and dynamic behaviour. The elements are interrelated, resulting in a mesh of elements. The behaviour of the mesh is calculated using the behaviour of the elements. By doing so, complex structures can be evaluated. Since geometry and material-behaviour need to be precisely known, FEM can only be applied in the final phase of the design process.

Mathematical expressions are used in every phase of the design process. They are used in the early abstract phases and results will be approximations. Rough cost calculations, for instance, can be made in the early phases of product design [Li et al., 1993]. They are also used in the concrete phases of the design process and, there, results will be more precise. Detailed product object designs, for instance, can be modelled in a FEM-model.

Another possibility to model the object design is the scale model. The object design is realised before all design decisions have been made. A scale model, therefore, is a concrete system representing (modelling) an object design, whereas all other modelling techniques model the object design as an abstract system. Scale models are often used in car design. The outside car geometry having been designed, other design decisions still need to be taken. Scale models are not only better suited to mental simulation, but sometimes other evaluation possibilities exist too. The car scale model can be used in a wind tunnel test to evaluate its aerodynamic behaviour. Architecture also often makes use of scale models.

These are used for communication, mental simulation purposes and, in special cases, for wind tunnel tests.

Iconic, symbolic and scale models all are used in the product design process. In the early abstract phases of the design process, the use of iconic models prevails. In the more concrete phases, the use of more formal techniques wins ground. Communication is made unambiguous and evaluation possibilities increase. Expensive iteration can be avoided. Storage and collection of previous object designs are improved. The development of even better product modelling techniques can greatly improve the product design process. Recent developments show an increasing interest in the modelling of the product object design in the early phases of the design process (for example [Andersson, Hugnell, 1991; Will, 1991]).

2.2.2. Production System Modelling

The modelling of products has been discussed in the previous Section. Most design research is done on products. The modelling of products, therefore, is better developed than the modelling of production systems. Two categories of production system models can be distinguished: continuous models and discrete-event model. Continuous modelling is more advanced than discrete-event modelling, because of the lack of discrete-event modelling theory. The modelling of production system object designs has emerged from the sketching stage in recent decades. Still, even the Caveman's Design Approach is widely applied.

The modelling of production systems will be treated in the same way as the modelling of products. Two types of models will be discussed: iconic models and symbolic models will be treated. Scale models will not be discussed in this Section, because of their scarce application.

The use of iconic models is widespread in production system modelling. Schemes and diagrams to model the material flow in a production system have been proposed. The Sankey-diagram is an example of this [Balkestein et al., 1987]. Another example is the lay-out or the floor-plan of an industrial system. Handbooks on production system design and analysis present numerous examples (for example [Buffa, Sarin, 1987; Chase, Aquilano, 1992]). A representation technique that can be used on a higher level of design abstraction is $IDEF_0$ [Wu, 1992].

Most of the iconic models have been developed for the analysis of existing production systems. The degree of design abstraction used in the modelling techniques, therefore is low. Although some iconic models have been proposed for more abstract phases of the design process, no clear definitions have been given. It remains unclear as to where and when they should be used. In Chapter 4, iconic models will be proposed for all phases of the production system design process.

The second class of modelling techniques produces symbolic models. Symbolic modelling techniques use some formal language to model the object designs. Symbolic models, therefore, consist of mathematical expressions that can be evaluated. Iconic models are mostly used for communication purposes. Evaluation can take place with mental simulation. Symbolic models can be evaluated in a more formal way. Symbolic models, however, are often less suitable for communication purposes. Following, some examples of symbolic modelling techniques will be given.

The use of symbolic modelling techniques for production systems started with the use of mathematical expressions to model the behaviour of production processes. Differential equations, for example, are used to model the behaviour of a single process. Recently, intelligent techniques have been developed to model the behaviour of complex production processes. Neural nets, for instance, can be used for the modelling of complex non-linear processes [Willems, 1994].

The modelling of a collection of processes has become possible with the introduction of advanced simulation techniques. Markov chains [Langrock, Jahn, 1979], simulation languages as Simula [Birtwhistle, 1979] and GPSS [Gordon, 1969] can be used to model and evaluate the behaviour of production processes. Integrated simulation packages have been developed to improve evaluation possibilities. Examples are ExSpect [Van Hee et al., 1988], based on Petri-nets [Petri, 1962] and Processcalculus [Rooda, 1991a,b,c; Wortmann, 1991], based on the process-interaction approach. The integration of intelligent techniques as rule-based systems [Vaes, 1994] and neural nets [Willems, 1994] into simulation packages has further improved modelling possibilities.

The use of discrete-event symbolic models is not widespread. The processing industry invests much effort in the development and use of continuous symbolic models. The use of symbolic models in discrete industry still is rare. There, the use of simulation techniques, introduced in the early seventies, is slowly gaining acceptance.

2.2.3. Conclusion

The modelling of products and production systems has been discussed in the previous Sections. Generally, modelling techniques are further advanced in product design than in production system design. Recently, however, much research has been done on evaluation techniques for production systems. Consequently, formal modelling and evaluation techniques are available for both product and production system design.

Most of the modelling techniques, however, are directed towards concrete phases in the design process. Both in product and production system design the abstract phases of the design process get little attention. Recently, more attention has been directed to the modelling of conceptual phases for product design. Object designs in abstract phases of the production system design process can be modelled using iconic modelling techniques. Their use, however, is rare, because no structure is available. Modelling techniques will be discussed in Chapter 4 in more detail.

The use of formal modelling and evaluation techniques is an important step forward. Advanced modelling techniques improve communication. Evaluation can take place before implementation. Expensive iteration can be avoided. Systems that are potentially dangerous can be evaluated in advance and risks can be calculated before use. The use of more formal representations is a first step towards a systematic approach to design. A second step involves the more systematic view on the design process. As formal models of the object design have only sparingly found their way to design practice, models of the design process are even more rarely applied. Nevertheless, research on the modelling of the design process has provided many interesting insights.

2.3. Modelling of the Design Process

The modelling of object designs has been discussed in the previous Section. This discussion revealed the need for the use of formal representation techniques in the design process. The use of formal representations results in unambiguous communication means and in improved evaluation possibilities. This is a first step towards systematic design. A second step involves the use of more formal models of the design process. Models of the design process as presented in literature will be discussed in this Section.

The number of publications on design research has grown exponentially in the last two decades. It is therefore impossible to list all published approaches, theories and methods. An outline of the most relevant design schools will be given. Unavoidably, many interesting publications will not be covered in this survey. The publications that are mentioned, however, in this Chapter are believed to be representative of the different design schools.

Design schools can be differentiated using the level of detail in their design process model. The simplest design process models focus on the phasing of the design process, whereas the most advanced approaches aim at the modelling of human decision-making using the laws of logic. The different design schools will be discussed in increasing level of sophistication. Firstly, the phasing of the design process will be discussed. Secondly, the development of detailed design methods will be discussed. Thirdly, general design methods will be treated. General design methods are valid for the entire design process, whereas detailed design methods are valid only for a small area. Fourthly, attention will be given to cognitive research. This Section will be completed with conclusions concerning the modelling of the design process.

2.3.1. Phasing of the Design Process

The design process is the process of decision-making concerning some object design. This decision-making process can be structured by the introduction of phases. The phasing of the design process will be discussed in more detail in Chapter 3. There, theory on the phasing of the design process will be presented. Here, a survey of various approaches will be given. Firstly, some reason to introduce phases in the design process will be given. A more elaborated discussion can be found in Chapter 3.

Empirical research showed that designers tend to spend little time in the early phases of the design process. Most time is spent in the detailing of concepts. These concepts are sometimes chosen within minutes, whereas the detailing takes hours [Stauffer et al., 1987]. The introduction of phases in the design process can avoid this, because the designer is forced to spend time on different levels of design abstraction. Lines 1 and 2 in Figure 2.2 illustrate this. The empirical research presented in Chapter 6 will discuss this in more detail. Another reason for the phasing of the design process, is the introduction of (standard) design documents. At the end of phase, a design document is made. These documents improve communication and evaluation.

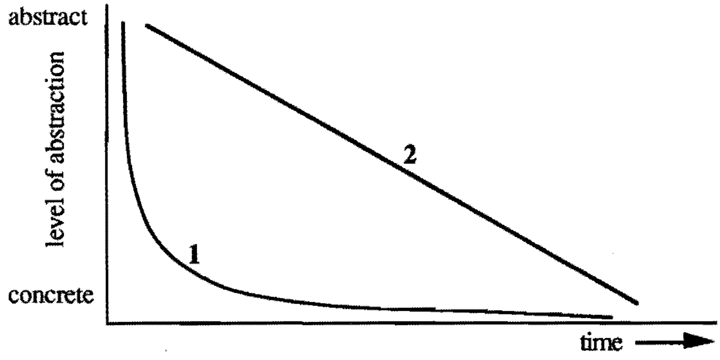


Figure 2.2. Different approaches to the design process.

The phasing of the design process has predominantly been a German occupation. Researchers in other countries, however, have also examined the phasing of the design process. Pahl and Beitz give a survey of German design research [Pahl, Beitz, 1984].

Hansen and Koller give stepwise procedures to tackle design problems. Rodenacker distinguishes four phases: (1) Clarification of the task; (2) Function of a machine; (3) Physical process; (4) Form design features. Roth also proposes three phases: (1) Task-formulation phase; (2) Functional phase; (3) Form design phase.
VDI-guideline 2221 proposes four phases: (1) Clarification of the task; (2) Conceptual design; (3) Embodiment design; (4) Detail design [Pahl, Beitz, 1984; VDI, 1986]. The Twente method proposes three phases: (1) Function; (2) Working principle; (3) Form [Van Den Kroonenberg, Siers, 1983]. Dixon has proposed a taxonomy of mechanical design problems. These design problems are on five different levels of abstraction. This proposal, therefore, can be seen as a phasing of the design process: (1) Conceptual design; (2) Phenomenological design; (3) Embodiment design; (4) Configuration design; (5) Parameter design [Dixon et al., 1988].

Table 2.1. Different approaches to the phasing of the design process.

<table>
<tr><th>Roth</th><th>Twente method</th><th>Rodenacker</th><th>VDI - 2221</th><th>Dixon</th></tr>
<tr><td>Task formulation phase</td><td rowspan="2">Function design</td><td>Clarification of the task</td><td>Clarification of the task</td><td>Conceptual design</td></tr>
<tr><td rowspan="5">Functional phase</td><td rowspan="3">Function of a machine</td><td rowspan="3">Conceptual design</td><td rowspan="2">Phenomenological design</td></tr>
<tr><td rowspan="5">Working principle design</td></tr>
<tr><td rowspan="2">Embodiment design</td></tr>
<tr><td rowspan="4">Physical process</td><td rowspan="4">Embodiment design</td></tr>
<tr><td rowspan="4">Configuration design</td></tr>
<tr><td rowspan="4">Form design phase</td></tr>
<tr><td rowspan="3">Form design</td></tr>
<tr><td rowspan="2">Form design features</td><td rowspan="2">Detail design</td></tr>
<tr><td>Parameter design</td></tr>
</table>

Table 2.1 shows that there is no universally accepted phasing of the design process. Not only does the number of phases differ, but also the names given to the various phases are not consistent. Conceptual design in one approach is called functional design in another. Besides this, phases overlap. The overlapping suggested in Table 2.1 is partially caused by the presence of a task clarification phase in some proposals and its absence in others. The reason for this lack of general understanding is the fact that different design problems

and different designers require different phasing of the design process. Theory on the phasing of the design process will be discussed in Chapter 3. This theory will be used in Chapter 4 to propose phases for different subsystems of an industrial system.

The phasing of the design process has been discussed in this Section. Next, the development of detailed design methods will be discussed.

2.3.2. Detailed Design Methods

The phasing of the design process has been discussed in the previous Section. Now, detailed design methods will be treated. A detailed design method is a method that supports decision-making on a relatively small area. General design methods, which will be discussed in the next Section, are valid for every possible design decision.
A connection between the use of detailed design methods and the use of phases has only been described for product design. Making this connection for the entire industrial system would improve the quality of the design process, because the designer is guided even further in his decision-making process. Not only would the designer design on all levels of design abstraction, he would also be supported in his decision-making by detailed design methods.

Many of the design methods have been developed for product design. Methods, for instance, for the optimisation of product object designs have been reported (for example [Burnell, Priest, Briggs, 1991; Lee, Chen, 1991; Lee, Wang, 1992]. Design methods have been developed for different phases in the design process. Traditionally, more concrete phases have been given attention. Configuration design is described by Ramaswamy, Ulrich and Kishi [1991]. A method to support parameter design has been described by, for example, Otto and Antonsson [1991]. Recently, conceptual design has received more attention [Spillers, Newsome, 1989; Waldron, Waldron, Owen, 1989; Faltings, 1991; Welch, Dixon, 1991; Hundal, Langholtz, 1992].

Another class of product design methods pays attention to the relationship between product and production system design. These design methods are part of the Concurrent Engineering approach. The designer takes care of consequences for the production systems while making design decisions for the product. The conventional Sequential

Engineering approach lets designers first design the products, relatively independently of the production system. Later, in the production system design process, problems arise, because expensive redesign is necessary. The objective of Concurrent Engineering is to avoid these expensive solutions by studying the consequences in advance. The use of appropriate design methods can help in implementing this approach.

One of the first design methods that addresses the consequences for the production system, is Design for Assembly [Boothroyd, Dewhurst, 1983]. The product design is optimised for assembly. The reason for developing this method was the observation that much of the production cost was made in assembly. Its objective is to diminish the number of parts, so that assembly will be easy and cheap. The designer is expected to take care of other aspects, like the possible increasing production costs. Integrated parts may be easier to assemble, but production may be more expensive. The net benefit, therefore, can be negative. Design for Assembly is widely applied in industry and has led to numerous spectacular results (for example 79 % cost reduction in a latch mechanism assembly [Bedworth et al., 1991]).

Countless other 'Design for X'-techniques have been developed. Some examples are: Design for Die-casting [Poli, Shanmugasundaram, 1991]; Design for Environmentability [Navinchandra, 1991]; Design for Quality [Nichols, 1992]; Design for Serviceability [Gershensson, Ishii, 1991]; Design for Recycling [Beitz, 1991]. All 'Design for X'-techniques study one aspect of the relation between product and production system design. The designer is expected to take care of other aspects. The thoughtless use of these techniques can, therefore, lead to sub-optimal results.

Many design methods have been developed and are used in practice. The relation, however, between the methods is still left to the individual designer. Currently, no structure of the design process is available in which all design methods can be placed. Such structure of the design process could help the designer in deciding which design method to chose and, consequently, which design decision to take.

Various detailed design methods have been discussed in this Section. Next, general design methods will be discussed. These can be used throughout the design process, whereas detailed design methods are applicable only in a small well-defined area.

2.3.3. General Design Methods

After the discussion of detailed design methods that are valid for a small area, general design methods will be treated. General design methods are valid for every design decision. They can be used throughout the design process for every possible object design. A number of approaches have been chosen. These will be discussed successively.

Axiomatic Design is an attempt to formalise the support of the decision-making process [Suh, 1991]. Suh has formulated two Axioms and has derived rules for the design process. The first axiom is the *Independence Axiom*: an optimal design always maintains the independence of functional requirements. The second axiom is the *Information Axiom* that states that the information content of the design should be minimal. Axiomatic Design leaves the decision-making process to the designer. The designer is directed by a set of general rules, derived from the two axioms.

A different approach is chosen by Altshuller. The Algorithm for the Solution of Inventive Problems (ASIP) is based on the Theory for the Solution of Inventive Problems (TSIP). The functional requirements are analysed and represented in some formal way. Physical, technical and administrative antinomies are eliminated using so-called *inventive tricks*. ASIP has been implemented in the Inventive Machine [Altshuller, Williams, 1984].

Many other techniques have been developed supporting the creative process. These techniques can be used in all situations where a problem needs solution. These techniques, therefore, can be used throughout the design process. Well-known techniques are Brainstorming, Method 635, Synectics, Delphi Method [Pahl, Beitz, 1984] and Conceptual Blockbusting [Adams, 1979]. A technique that has been developed to support decision-making in the design process is the Morphological Analysis [Zwicky, 1969]. A systematically constructed list of solution principles is given. Using this technique, principle solutions will not be overlooked.

Besides the more formalised methods and techniques mentioned above, many rules of thumb are used in design practice. Do's and don'ts in design are used by experienced designers. The formalisation of this design knowledge will greatly improve the quality of object designs and design education.

General techniques in design have been discussed in this Section. The general techniques can be used throughout the design process. It has been shown that many techniques have already been developed. Continued formalisation of design knowledge, however, will further improve design results. Next, cognitive research will be discussed. Models of the human decision-making process will be treated.

2.3.4. Cognitive Research

Having surveyed the phasing of the design process as well as detailed and general design methods, attention will now be paid to the modelling of the human decision-making process. The design process is in its essence a decision-making process. These decisions are made by human designers. Formal design methods can be developed for some well-understood areas. Section 2.3.2 showed some examples of these. Another possible way to formalise the design process is to start at the quintessence of design, the human decision-making process.

Cognitive design research is a diverse and young research field. Many different approaches have been chosen. To attempt a survey of this research is even more difficult than it was for the research discussed in the previous Sections. Moreover, most of the cognitive research is not performed for design purposes.

The search for an appropriate model of the human thinking and decision-making process has yielded many useful techniques. Rule-based systems and neural nets are only some of the examples of the resulting techniques. These techniques can be used in detailed design methods to solve complex design problems. Knowledge on the object to be designed is combined with knowledge on (human-like) decision-making.

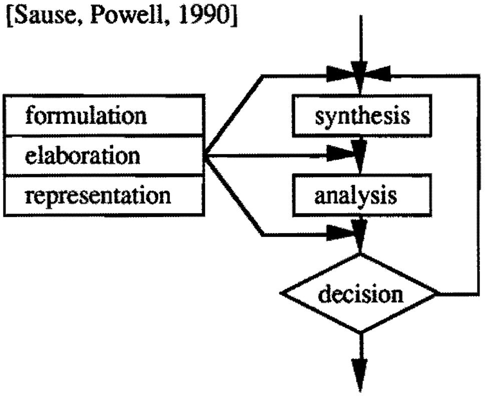
A problem concerning the modelling of the human decision-making process is the introspection problem. Many researchers have formulated so-called decision cycles that are based on their own personal experience with design. Table 2.2 shows a selection of five different decision cycles that have been proposed in literature. Often, these are not based on empirical research.

Table 2.2. Decision cycles in the design process.

[Andreasen, 1991]
1. formulate the problem
2. determine criteria
3. seek solution
4. evaluate and choose
5. carry out

[Frost, 1992]
1. awareness of the problem or opportunity
2. definition of problem
3. generation of solution concepts
4. initial development of concepts to the point where evaluation can validly occur
5. evaluation of concepts
6. selection of concepts for adoption
7. detail design
8. communication

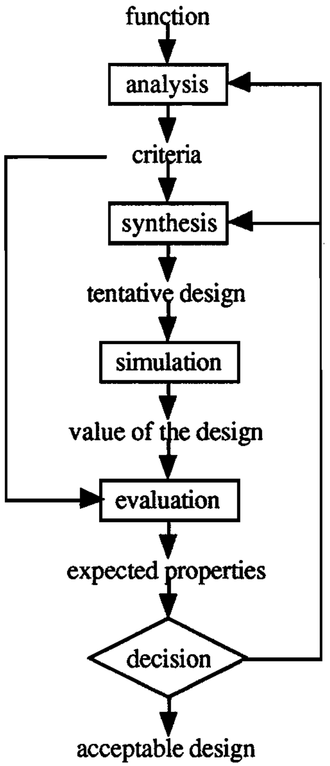
[Sause, Powell, 1990]



[Takeda, Tomiyama, Yoshikawa, 1990]
1. awareness of problem
2. suggestion
3. development
4. evaluation
5. conclusion

Continuation Table 2.2. Decision cycles in the design process.

[Eekels, Roozenburg, 1992]



A general decision making cycle can be deduced from the proposals in Table 2.2. Four steps can be observed: (1) analysis, (2) synthesis, (3) evaluation, (4) decision. This general decision cycle will be used in this dissertation. The decision cycle used in this dissertation is equal to the decision cycle defined by Eekels and Roozenburg, with the exception that simulation and evaluation in their decision cycle are replaced by evaluation. Simulation, mentally or formally, however, is part of the evaluation step. Figure 2.3 shows the decision cycle that will be used throughout this dissertation.

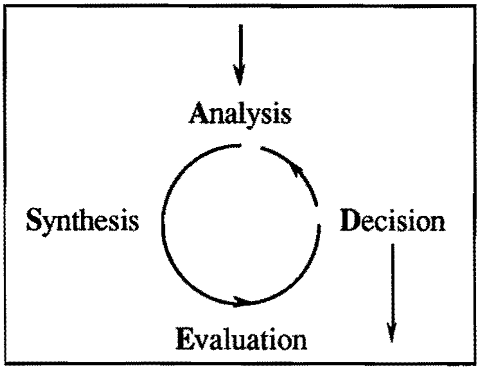


Figure 2.3. The decision cycle used in this dissertation.

A basic problem-solving cycle has been proposed by De Boer [1989]. A decision cycle is completed with implementation and review steps to formulate a problem solving cycle. Five steps were proposed: (1) diagnose, (2) plan, (3) develop, (4) implement and (5) review. In this dissertation, only the decision cycle will be used.

Other researchers use empirical research to model the human decision-making process. Protocol Analysis [Ericsson, Simon, 1984] is used to model human thinking processes. The designer is asked to express his thoughts while designing. Observations are then generalised [Adelson, 1989; Visser, 1991, 1993; Christiaans et al., 1993; Dorst, 1993; Fricke, 1993]. So far, no detailed theory has resulted from this research.

Some researchers use the laws of logic to model the human decision making process. A group of Japanese researchers has formulated the Extended General Design Theory [Tomiyama, Yoshikawa, 1986; Takeda et al., 1990]. Logic is used to model the design process. Practical implications are, however, currently limited.

The attempt to formalise the human decision-making process has led to many partial successes. Design methods have been developed that are based on the insights gained in this research. Some of these design methods have been discussed in the previous Section. So far, no detailed design theory has been formulated that is able to describe the human decision-making process in full detail.

2.3.5. Conclusion

The modelling of the design process has been discussed in the previous paragraphs. The phasing of the design process has been treated. The different number of phases was signalled. No general understanding can be found in literature. Next, different detailed design methods have been discussed. The design methods support the human decision-making process concerning a small well-understood area. The large quantity of design methods was signalled. No general structure, however, can be found in literature. General design methods have been discussed next. General sets of rules and techniques have been presented that can be used throughout the design process. Then, cognitive research has been treated. Some of the cognitive research is not based on empirical research. Other approaches are, however promising, not yet detailed enough. The decision cycle will be used in this dissertation to model human decision-making in design. Techniques, originating from cognitive research can be used successfully in the development of design methods.

The research on the design process is a large and diverse field. Many different approaches have been chosen. Still, much research needs to be done. The structure of the design process, for instance, requires better understanding. Design methods can still be perfected and expanded, and more understanding of the human decision-making process is required. The next Section will discuss research opportunities that have been signalled in this Chapter and there, the choices that have been made for this research project will be treated.

2.4. Conclusion

The modelling of object designs and the design process have been discussed in the previous Sections. Modelling techniques for both products and production system are available. Iconic models exist for all phases of the design process. The symbolic models that have been developed can only be used in the more concrete phases of the design process. No clear definition is given as to where the various models should be used. Therefore, the use of modelling techniques is rare and unstructured.

Next, the modelling of the design process has been discussed. Phases have been introduced in the design process. Different numbers of phases have been proposed by different authors. No general understanding can be found. A large quantity of detailed design methods has been developed. No structure, however, is given. The designer decides when to use which method. Cognitive research has studied the human decision-making process in design. Many interesting results have been reported. A full understanding of the human decision-making process is still a long way off.

Roughly, two research areas deserve more attention. Firstly, the research on human decision-making will lead to a better understanding of design processes and eventually to better object designs. Secondly, research can be done on the designing of design processes. Designers should not only pay attention to the design of the object, but also to the design of the design process. This research should clarify the use of modelling techniques in the design process. It should resolve the confusion in for instance the phasing of the design process. Furthermore, some concepts in design theory need clarification and definition. Next, the design of the design process should structure and systematise the use of design methods.

The designing of the design process will be treated in this dissertation. This will result in a structured design process. The industrial system design process is divided into several interdependent steps that need to be performed consecutively. The decision making process then is guided, but, nevertheless, decision-making stays in the designer's hands. Intuition and creativity, therefore, are not banned, but structured. The structured design process then consists of a series of decision cycles. Design process models, as discussed in Section 2.3, can be used to model this decision making. Decision-making will involve the four steps identified above: (1) analysis, (2) synthesis, (3) evaluation and (4) decision. Methods and techniques need to be developed to support the decision making process in all four steps in the decision cycle. The development of these methods and techniques in the structured industrial system design process will be discussed in Chapter 4.
General and detailed design methods and techniques can thus be used in structured design. They support one or more steps in the decision cycle.

The structuring of the design process will be discussed in the next Chapter. Chapter 3 discusses design methodology. It deals with the way to structure design processes. The structuring of the industrial system design process is treated in Chapter 4. Chapter 4, therefore, discusses a design method. It deals with the way to design an industrial system.

Chapter 3

Structuring the Design Process

In the previous Chapter, the need for a structured approach to the design process was signalled. A structured approach would increase the quality of the object design. The design process would be overseen more easily and design decisions would be taken with greater care, because the designer would be better aware of the consequences of his decisions. The structuring of the design process is therefore discussed in this Chapter.

The theory developed in this Chapter can be used to structure design processes. Chapter 4 will discuss the application of this theory for the industrial system design process. There, a structured design method will be proposed. The design process will then consist of a structured series of decision cycles. Decision-making can be done supported by methods and techniques for all four steps in the general decision cycle. The development of supporting methods and techniques will be treated for the industrial system design process in Chapter 4.

A system theoretical approach is chosen to describe the design process. The concepts defined in system theory will be used throughout this dissertation. Therefore, a short revision of system theory will first be given. After this, a new concept will be introduced to make system theory suitable for the structuring of design processes. Next, the structuring of the design process will be discussed using the system theoretical concepts. This will lead to the introduction of the design cube. Design processes can be structured by choosing a proper division of the three axes of the design cube. The three axes will be discussed separately.

The structuring of design processes is discussed in Sections 3.2 to 3.4. Sections 3.5 to 3.8 discuss the theory developed in these sections. The concepts defined in this Chapter can easily be confused. Possible confusion will be discussed in Section 3.5. A procedure to structure the design processes will be discussed in Section 3.6. This procedure will be used in the next Chapter to structure the design process of industrial systems. Section 3.7 will present a discussion on the feasibility and usefulness of the structuring of design processes. Finally, the Chapter will be completed with some conclusions concerning the structuring of design processes.

3.1. System Theory

The model of the design process presented in this Chapter is based on system theory. Consequently, system theoretical concepts are used throughout the dissertation. These concepts need clarification and definition, however, and so a summary of basic system theory will be given. These concepts do not suffice for the structuring of the design process. Therefore, secondly, system theory is extended with an extra concept: design abstraction. This will result in the introduction of the design cube.

Basic System Theory

Many definitions have been given for a system. The word system stems from the Greek 'systema', from the verb 'synistanai': to bring together, combine. The Webster dictionary defines system as: (1) a complex unit formed of many often diverse parts subject to a common plan or serving a common purpose; (2) an aggregation or assemblage of objects joined in regular interaction or interdependence [1986]. A system can also be defined as a set of elements standing in interrelations [Bertalanffy, 1968]. Van Aken defines a system S as a set of elements E with a set R of relations between the elements, R having the property that all elements of E are directly or indirectly related [1978]. A system is a collection of entities together with the collection of relations that exist between the entities [Kramer, De Smit, 1991].

In a more formal way, a system can be defined as following [Kramer, De Smit, 1991]:

1. a collection of entities in the system: W.
2. a collection of entities in the environment: E.
3. a collection of relations between entities in the system: R_{ww}.
4. A collection of relations between entities in the system and the environment: R_{ew}.

Set theory then gives: system $S = \langle W, E, R_{ww}, R_{ew} \rangle$ [De Leeuw, 1974]. Finally, a system can be defined as, dependent on the researcher's objectives, a collection of elements to be distinguished in the universe. These elements are interrelated and have relations with elements outside the system [In 't Veld, 1992].

The concept of element (or entity) is often mentioned in these definitions. Van Aken defines an element as the smallest entity considered in an argument. An entity is a basic element in the researcher's investigations to which he ascribes a collection of attributes [Kramer, De Smit, 1991]. Other authors give similar definitions.

A system theoretical concept that also needs definition is the environment of a system. The environment of a system S consists of all elements outside S [Van Aken, 1978]. Other authors give similar definitions.

Another important concept in system theory is the relation or relationship. A relation describes interdependence between elements [In 't Veld, 1992]. De Leeuw defines a relation as following: 'One can speak of a relation if a change in the value of an attribute of an entity results in the change of the value of another entity [1974]'.

A sub-system is a subset of the collection of elements in the system. All relations between the elements remain [In 't Veld, 1992]. A sub-system of a system S is a subset of E (the set of elements of S) with all the attributes of the elements in question [Van Aken, 1978]. An aspect-system is a subset of all relations in the system. All elements are considered [In 't Veld, 1992].

An attribute is a property [Van Aken, 1978]. An element is distinguished by means of its attributes [Kramer, De Smit, 1991]. An attribute is a quality, a character, or characteristic ascribed usually commonly: (1) a characteristic either essential and intrinsic, or accidental and concomitant, (2) a quality intrinsic, inherent, naturally belonging to a thing or person [Webster, 1986].

Another important system theoretical concept is structure. Structure can be defined as the collection of relations [De Leeuw, 1974]. In 't Veld also defines structure as the collection of relations. Here, a distinction is made in internal and external structure. The internal structure is the collection of relations between all elements within the system. The external structure is the collection of relations of elements in the system with elements outside the system [In 't Veld, 1992]. Other authors give similar definitions.

The definitions that have been presented above will be used in this dissertation. The definitions do not exclude each other and are often interchangeable. Many other concepts have been introduced in system theory. They can be defined and explained using the basic concepts mentioned above.

These system theoretical concepts can be summarised in three basic concepts: systems, attributes and relations. Elements, sub-systems and systems are similar concerning the fact that they consist of one or more elements. They have attributes and relationships with other elements (sub-systems and systems). If the relations between the elements are seen as attributes of those elements, a system theoretical description of any object can be visualised in a plane. This is demonstrated in Figure 3.1. One axis in Figure 3.1 concerns the (sub-) systems and elements, whereas the second axis concerns the attributes, describing the various (sub-) systems. Relations between (sub-) systems are also incorporated in the attributes axis. Any object can be described using this plane.

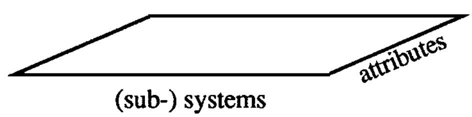


Figure 3.1. Representation using sub-systems and attributes.

Extension of Basic System Theory

Object designs can also be described using these system theoretical concepts. An object design can be visualised in a plane like Figure 3.1. The description, however, of the object design changes during the design process. It will necessarily be rough in the beginning of the design process, and complete at the end of the design process.

In other words, the object design is abstract in the beginning and concrete at the end. Knowledge refers to many possible objects in the beginning, whereas it refers to one possible object at the end. The object design, therefore, is transformed from abstract to concrete. This implies that, in order to describe the design process of an object, a third axis needs to be added to Figure 3.1. This third axis represents the level of *design abstraction* of the knowledge describing the object design.

Now, a three-dimensional figure results: the design cube, see Figure 3.2. The three axes of the design cube are: *attributes*, *design abstraction* and *(sub-) systems*. Every plane perpendicular to the design abstraction axis is a description of the object design at a certain level of design abstraction. Design can, therefore, be seen as the process of moving from the upper plane in the design cube to the lower plane[1]. Roughly, time goes from top to bottom in the design cube. The design cube can be used to structure design processes. This will be shown in the rest of this Chapter.

[1]The designer can also leave the design cube at a higher level of design abstraction. Not all design decisions have been made by the designer. This implies that some design decisions still need to be made during realisation.

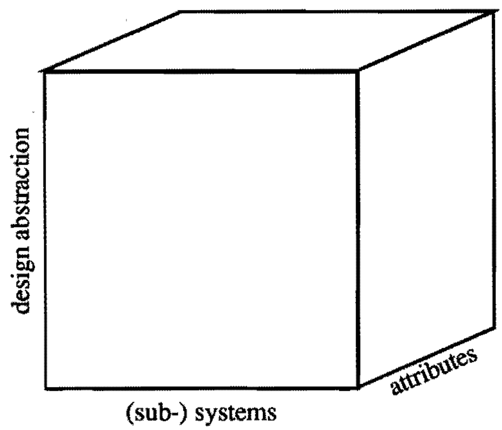


Figure 3.2. The design cube.

The three separate axes will be treated in this Chapter. Firstly, the attributes will be discussed. A model of the object design and the design process is presented in this Section. Secondly, design abstraction will be discussed. Theory on the phasing of the design process is presented in this Section. It is shown that the design process can be divided in an objective definition phase and the rest of the design process. A basic procedure is presented for the objective definition. Then, the phasing of the rest of the design process is discussed. Thirdly, the (sub-) systems and elements are discussed. The division of the object design into separate sub-systems is discussed in this Section.

3.2. Attributes

In this Section, the design process will be modelled using a network of attributes. This network describes the object design. It is collection of attributes, modelling the object design, interconnected with a collection of relationships. It is a representation of the laws of nature. All relations, known or unknown, formalised or not, are represented in this network. Figure 3.3 shows part of the network of attributes. The relationships between the attributes are similar to the relations defined above. There, relationships between attributes of different elements were discussed. Here, relationships between attributes of one element are treated.

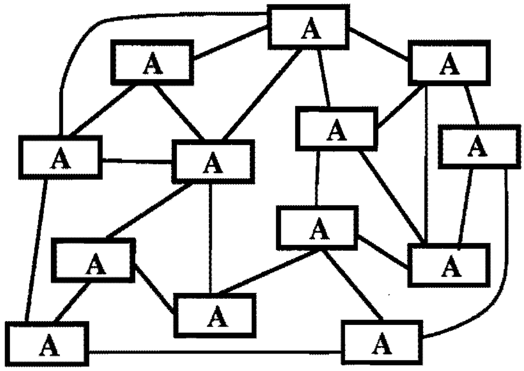


Figure 3.3. Part of a network of attributes.

A car for instance, can be modelled by listing all of its attributes. For example, its mass is 1100 kg, its colour is metallic-green and its height is 1.40 m. A large set of attributes is required to model this product. These attributes are interrelated. Mass, volume and material density are related through the relation Mass = Volume * Density. Material, therefore, could be chosen as a result of mass and volume constraints. In reality, relations are much more complex. Material choice is not only related to mass and volume, but also to strength, corrosion resistance, cost, appearance, etc.

The network can be used to model the design process. The attributes in the network can have all possible values in the beginning of the design process. The network may refer to any conceivable object. Knowledge on the object to be designed, encapsulated in the network, is called abstract. At the end of the design process, the network refers to one particular object. The attributes in the network all have certain values modelling the object design. Knowledge on the object design is called concrete. The design process starts with abstract knowledge on the object design and ends with concrete knowledge[2].

Design, now, is seen as the filling in of the network of attributes. The designer chooses values for the various attributes, which are then propagated throughout the network by the relationships. This will be illustrated with a small example of product design. The requirements for a particular product are a certain strength, corrosion resistance and cost. In this design process, the designer starts with the design of the product's geometry. By doing so, the products volume is fixed at 4 dm^3. For reasons of strength, corrosion

[2]See the note on abstract and concrete knowledge in chapter 2.

resistance and cost, the only possible material is stainless steel. The density now is fixed at 7.9 kg/dm^3, and mass in turn at 31.6 kg.

The decision-making process itself can be modelled using the decision cycle, discussed in Chapter 2. Four steps were identified. The first step involves the analysis. Relevant attributes and their relations are investigated. Next, synthesis when actual decision-making takes place. Design decisions are made based on the knowledge gained in the analysis step. The network of attributes has been filled in by the making of design decisions. The third step involves the evaluation of the new object design. This step tells the designer the quality of the object design. In the final step, the designer decides whether to accept the design decisions or not. Methods and techniques can be developed to support one or more steps in a decision cycle.

Structuring the attributes axis can be done by dividing the axis into separate sets of attributes. The designer, for example, pays attention to the different sets of attributes in a sequential way. Research on specific design problems should reveal which sub-set of attributes is relevant. Chapter 4 will deal with the relevant attributes in industrial system design. Cognitive research should reveal the way designers deal with the division of the attributes axis. In this Chapter, the attributes axis will not be structured.

Above, the designer only designed the product's geometry, strength, corrosion resistance and cost. The network of relations determined the product's material, volume, density and mass. In reality, the design process is much more complex. This complexity can cause contradictions in the attributes. *Iteration* is then required, and this will be discussed next.

Iteration

Sometimes, decisions are taken causing contradictions in the network of attributes. Iteration of the design decisions has become necessary or, in other words, *redesign* is appropriate. This will, again, be illustrated with a small example of product design. The requirements for this product are a maximum weight of 30 kg, a particular strength, corrosion resistance and cost. The designer designs geometry in the same way as in the previous example. Mass is fixed at 31.6 kg. Now, a contradiction has risen. Mass is 31.6 kg and should be below 30 kg. Iteration is necessary.

Iteration is the reconsideration of design decisions. A different geometry may be designed or another maximum weight should be chosen. Also, a different material may be chosen. This may cause another contradiction. Cost may be too high or strength too low. A different maximum cost may be necessary or a different minimum strength. Different attributes may also be changed simultaneously. The designer should decide on the appropriate alteration.

Here, a comparison with the general decision cycle can be drawn. The first step in the decision cycle involves the analysis of the initial object design. All relevant attributes and their relations are investigated. Next, a design decision is made in the second step. Thirdly, the new object design is evaluated using the knowledge the designer has on the object design. The designer decides whether to make the design decision or not in the fourth step. The knowledge on the design object is used in the first and third step of the general cycle. If this knowledge is incomplete or incorrect, contradiction may arise in a later phase. Iteration is then required.

The number of attributes and relations is too large to be assimilated by the designer. Iteration, therefore, is natural and practically unavoidable. The necessity for iteration may be reduced by consideration of the relevant attributes. Also, relations between the attributes need to be known in order to avoid iteration. A 'good' designer, therefore, will have a better model of attributes and their relationships than a 'bad' designer.

The design process has been modelled as decision-making concerning a network of attributes, modelling the object design. The evolution of the object design can be modelled by a design cube. The design process is the process of moving from the upper plane in the design cube to the lower plane. Actual decision-making can be modelled by the general decision cycle, defined in Chapter 2. The attributes axis has been discussed in this Section. The second axis, representing design abstraction, will be treated in the next Section.

3.3. Design Abstraction

Design can be seen as the filling in of the network of attributes. Decision-making in the synthesis step of the general decision cycle results in the network of attributes being filled in. In the beginning of the design process, knowledge is abstract and the network refers to many possible object designs. At the end of the design process, knowledge is concrete and the network refers to only one object design. Many decisions need to be taken between the objective definition and the end of the design process. Therefore, division into separate levels of design abstraction can be appropriate. Firstly, some reasons to introduce phases in the design process will be discussed. Secondly, some disadvantages will be treated. After this, theory on the phasing of the design process will be discussed.

Reasons for Phasing the Design Process

Many decisions are taken in a design process. Often a group of designers is working on an object design. Then, communication is essential but difficult. Evaluation of interim results may be required to avoid unnecessary iteration. Time management may require standard documents. Planning and control, especially of complex design processes, are difficult. In addition to these managerial issues, guidance may be necessary during the design process. Designers may be inclined to jump to conclusions and skip the essential abstract part of the design process. It is expected that all this can be improved with the introduction of phases in the design process.

Phases in the design process result in standard documents that can be used for evaluation, communication and time management. Planning and control of the design process are made easier, because the phases allow more overview and a better control. The designer is forced to explicitly model the conceptual model he has in his mind. By doing so, the object design can be evaluated by other designers, his client and the users of the object. In summary, the phasing of the design process may be sensible for reasons of focus of attention and design documents becoming available.
Empirical research is required to demonstrate the claimed positive effects. In Chapter 2, some empirical research has been presented. Chapter 5 contains an empirical test of the structured design process that is proposed in this dissertation.

Disadvantages of Phasing the Design Process

Besides the advantages, mentioned in the previous Section, some disadvantages should be mentioned. It will be shown below, that there is no fundamental reason for the introduction of a particular number of phases. Consequently, phasing should be tailor-made. Phases, proposed in the literature, are not flexible. These rigid phases may be difficult to follow, because of the iterative nature of a particular design problem (or designer). Also, many designers feel constrained by the phases. It is believed that the creative design process cannot be structured. The empirical research mentioned above should investigate these apparent negative effects as well.

3.3.1. Objective Definition

A first structuring of the design process can be achieved by considering the participants in the design process. Below, it is shown that there is a clear distinction between the objective definition phase and the rest of the design process. The difference between both phases can be traced to the one who sets or constrains the attributes.

In the beginning of the design process, the attributes can have any value. The designer will start by giving attributes certain values. There is, however, at this stage no reason to prefer a particular value above another. The reason for this is that the object design derives its right to exist from other systems. The raison d'être comes from outside the system to be designed.

The systems that take interest in the object design are called Interested External Systems (IES's). The IES's determine the initial values of a subset of the attributes. By doing so, the IES's constrain the object design. All valid object designs are within the constraints posed by the IES's. The best object design, however, still cannot be determined. The different attributes, therefore, need weighing. The best object design, therefore is always a trade-off.

The designer and his client will weigh the different attributes to be able to determine the best object design. No formal and objective techniques are known for this weighing. Techniques mentioned in Value Engineering [ASTME, 1967] or German Wertanalyse [VDI, 1976] can be used to reduce subjectivity. The weighed attributes originating from the IES's are called the objective of the object design.

Two distinct phases can be distinguished in the design process. The IES's determine the values in the first phase, whereas the designer determines the values of the attributes in the second phase. This fundamental difference allows the phasing of the design process into two distinct phases. The first is called the objective definition phase. Figure 3.4 shows this first structuring of the design process.

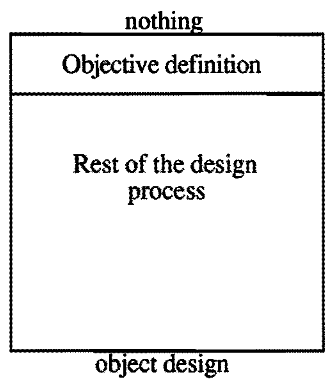


Figure 3.4. A first structuring of the design process.

Objective definition consists of three steps. The IES's are identified in the first step. The attributes to be constrained are identified in the second step. Here, the attributes are set by the IES's. By doing so, the hard constraints are set. Finally, the attributes are weighed in the third step. By doing so, the soft constraints are introduced. Figure 3.5 shows the basic three steps in the objective definition. This procedure is worked out in a method for industrial systems in Chapter 4. The method is demonstrated for a particular industrial system in Chapter 6. Here, the procedure for the objective definition is illustrated with a small example.

Three steps of objective definition
1. identification of Interested External Systems
2. setting of hard constraints
3. weighing of soft constraints

Figure 3.5. Three steps of objective definition.

The example deals with the objective definition for a hen-house. The first step in the procedure is the identification of the IES's. For this, it is necessary to identify the systems that interact with the hen-house in one way or another. The following IES's are identified: (1) owner, (2) chicken, (3) neighbour, (4) government. These IES's all have constraints for different attributes. Attributes like price, aesthetics, space, shelter, smell and noise are relevant in the design of the hen-house.

Some of these attributes cannot be optimised simultaneously. The owner's attribute of cost is optimised at the expense of the chickens' attribute space and the neighbour's attribute smell. A hen-house that optimises the government's attribute environmental disturbance will probably lead to an expensive solution. Therefore, weighing of the attributes is necessary. This will lead to different solutions. The optimal hen-house from the chicken's perspective will have lots of space, whereas the optimum for the neighbour will be small, odourless and aesthetic. The optimal hen-house from the owner's perspective may be small or large, dependent, for instance, on his profit demands. Many different hen-houses are possible, resulting from a different setting and weighing of the attributes.

Often, the objective definition phase cannot be finished before the start of the rest of the design process. It may be impossible to identify the constraints on all attributes. Furthermore, constraints on attributes may be constrained even further or even be changed. Consequently, objective definition and the rest of the design process are not necessarily executed successively.

3.3.2. Phasing of the Rest of the Design Process

Two phases have been introduced in the design process. The objective of the object design is designed in the first phase. The rest of the design process is done in the second phase.

The design process can be structured by the introduction of phases. The design process is divided into phases of different level of design abstraction. Above a certain well-defined level of abstraction the object design is in Phase P, below this level of abstraction, the object design is in Phase P+1. The introduction of phases in the design process requires the definition of these levels of abstraction at which an object design is transformed from Phase P to Phase P+1.

There is, however, no known fundamental reason to distinguish between different levels of abstraction. This implies that phasing of the rest of the design process is not based on any design theory. The network of attributes is filled in a continuous way. This is an essential point that needs illustration.

Sometimes, for instance, function is claimed to be an essential phase in the design process. It is, however, not clear to which extent the attributes are filled in. The function of a car is transport from A to B. This means that there is an attribute 'ability to transport' that is filled in. This, however, is not the only attribute that is constrained. Automobility is determined as well as safety, speed, weight, etc. The attribute 'ability to transport' clearly is not enough to define the function of a car. A clear definition of function, therefore, is arbitrary. It should, however, be said that other views on design can indeed result in an exact definition of function [Hubka, 1980].

Phasing of the design process can have its benefits. Above, advantages of phasing have been mentioned. The designer is guided in his decision making and the introduction of interim results can improve communication. Phasing, however, needs to be flexible. The designer cannot and will not make use of phasings that are too rigid.

The design process has been divided into phases in many different ways. The different proposals have been discussed in the previous Chapter. Table 2.1 showed phasings of the product design process. The different proposals for the phasing of the design process all have their validity. It is shown that this validity is not based on design theory, but on project management. This implies that the phasing is not universal, but dependent on the design problem and the designer. A complex design process may require many phases, whereas in a simple design process few phases may suffice. Phasing may be sensible in the design of a sophisticated system, whereas in the design of a domestic hen-house no phasing is required. The individual designer's needs can also play a role in the phasing of the design process. More research is necessary to investigate this relationship.

Any number of phases, therefore, can be used. Standard design documents should be defined. The level of abstraction of the structure and relevant attributes should be defined. A design phase is considered to be completed if the level of abstraction of the structure and the relevant attributes is reached and the design documents are made.

The phasing of the design process should be flexible and adaptable to the needs of both the designer and the design problem. A standard-phasing may be proposed that can be used in the majority of cases. This has the advantage of a standardised project management with standard documents. The designer may deviate from this standard-phasing in extraordinary situations.

The phasing of the design process has been discussed in this Section. The structuring of design processes concerning the level of design abstraction has been treated. Two phases have been introduced. The objective of the object design is defined in the first phase. The rest of design process is done in the second phase. Although no design theoretical reason can be given for a further phasing of the rest of the design process, phasing can be useful. Research on human thinking should reveal the relation between the designer, the design problem and the number of phases.

The next Section will deal with another aspect of the structuring of the design process. An object design can be divided into separate sub-systems to be designed in parallel. The fundamentals of the decomposition into sub-systems will be discussed.

3.4. Sub-systems

The first two axes of the design cube have been discussed. An object design can be modelled as a network of attributes. This network of attributes can be used in the structuring of the design process. Decision-making in the synthesis step is modelled as the filling in of attributes. Design abstraction has been discussed. The design process can be divided into a number of phases. Advantages, disadvantages and conditions have been mentioned. Next, the structuring of the third axis of the design cube will be discussed. A number of concepts concerning sub-systems will be treated.

At any moment in the design process, the designer may decide that the object design will itself consist of a set of object designs, together realising the objective. The system to be designed has been divided into separate sub-systems. In this Section, the division into sub-systems will be discussed in detail. The mechanisms that can be used in the division into sub-systems will be dealt with. Decomposition and composition are discussed in Section 3.4.1. Different design strategies can be followed using the division into sub-systems. Parallel and sequential design of sub-systems can be applied. These will be discussed in Section 3.4.2. The designer can choose a top-down or a bottom-up design process. The fundamentals of top-down and bottom-up design are discussed in Section 3.4.3. Firstly, some advantages and disadvantages to the division into sub-systems will be discussed.

Reasons for Division

Many reasons can exist for dividing the object design into sub-systems. The predominant one is to avoid complexity. An object design is most often too complex to design as one system. Industrial systems, organisations, products, etc. could not be designed without the division of the system to be designed into separate sub-systems. Computer systems consist of separately designed sub-systems or components. The hard disk is designed separately from the monitor and separately from the processing unit. Interfacing between separate sub-systems needs to be defined accurately.

Another important reason to divide the object design is the wish to have systems built in a modular fashion. Modularly designed systems are easily maintained. Malfunctioning

modules are easily replaced. Modular systems can be expanded more easily. An existing module can be replaced by a new module having the same but enhanced function. New modules can be added to give the system increased functionality.
Modular systems can have advantages in production. Modules are produced and kept in stock separately. Products are assembled to customers' demands. The production system produces at relative low cost with high product flexibility.

A third reason to divide the object design into separate sub-systems to be designed in parallel, is the possible gain in time. Design processes can be completed more quickly if separate sub-systems are designed in parallel. Designers work in parallel on smaller object designs, resulting in a design process evolving more rapidly [Van Bragt, 1989]. The design process does not automatically evolve more quickly when dividing the object design. Besides the parallel design of sub-systems, sequential design of sub-systems is possible. The possible advantage of a rapid design process disappears using sequential design. Parallel and sequential design will be discussed in Section 3.4.2.

Disadvantages to Division

The main disadvantage to the division of the object design is sub-optimisation. The sub-systems all are designed and optimised individually, leading to a collection of individually optimal sub-systems. These sub-systems put together will not necessarily produce a global optimum. The global optimum can only be attained with vast amounts of communication between designers, implying a non-divided design process.

An example of sub-optimal design can be given for industrial system design. There, products are sometimes designed separately from the manufacturing system. After the product design is completed, it is 'thrown over the wall' that exists between product and manufacturing system designers. The manufacturing system engineers then design the manufacturing system. This procedure has led to many sub-optimal industrial systems. Chapters 4 and 6 will go into this matter more deeply.

3.4.1. Decomposition and Composition

So far, no attention has been given to the operation resulting in different sub-systems. This Section will go into this matter more deeply. The newly defined sub-systems can result from a *decomposition* or a *composition* action. The attributes of these sub-systems are set in some way. Firstly, criteria for decomposition and composition will be discussed. Secondly, the decomposition action will be discussed. After this, attention will be given to the composition action. Finally, the interactions between sub-systems will be discussed in detail.

Reasons for the division into subsystems were mentioned above. In system theory, some decomposition criteria have been given. The latter, however, deal with the modelling of systems, whereas the former deal with design. Although there is a fundamental difference between the two sets of criteria, the latter set will also be discussed.

If a system is decomposed into two sub-systems, relations will exist between the two sub-systems. Decomposability-criteria have been developed in system theory. System boundaries are there, where the concentration of relations is smaller than elsewhere [Ulrich, 1968]. In 't Veld states four possible criteria. Firstly, a minimum interaction criterion: the boundaries are chosen such that interaction of temporary elements is minimal. Secondly, the number of relations over the boundary: the boundaries are chosen such that elements belong to a system with minimal external relations. Thirdly, the energy required to cross a boundary: boundaries are chosen such that the energy required to cross a boundary is greater than the energy transferring within system boundaries. Fourthly, the function of the system: boundaries are chosen such that the function of the system is easily described [In 't Veld, 1992]. Simon speaks of *nearly-decomposable* systems. Nearly-decomposable means that the short-term behaviour of the system is determined by the relations within the system, whereas the long-term behaviour is determined by relations outside the system [Kramer & Smit, 1991]. Van Aken defines a nearly-decomposable system as a system that can be partitioned into sub-systems with the property that the relations between the elements of each sub-system are stronger than those between elements from different sub-systems [Van Aken, 1978].

Again, it is stated that the decomposition criteria mentioned directly above are meant to be used in a modelling situation. The design situation, however, is related to this. After the designer has opted for decomposition, as a result of the reasons for division, he can use insights from the set of decomposition criteria to decide on the exact decomposition.

Decomposition

Decomposition of the object design into sub-systems to be designed individually, will result in set of newly defined sub-systems. Like the original system, these sub-systems have an environment. This environment consists of systems outside the system to be designed (system's IES's) and other sub-systems of the system, together forming the IES's of the sub-system. The environment will set the attributes of the newly defined sub-systems in the same way as in the objective definition, discussed earlier in Section 3.3.

Relations, however, are more complex after a decomposition action. This can be illustrated with an example. The maximum weight of a particular object design is fixed at 12 kg. The designer decides that this object design should consist of two sub-systems. Now, a number of possible strategies can be followed. Firstly, a maximum weight can be given to both sub-systems, together being 12 kg. Sub-system A may have a maximum weight of 8 kg and sub-system B of 4 kg. Both sub-systems can have of a maximum weight of 6 kg, etc. Another possibility, however, is that no individual maximum weights are set. The maximum weight for both sub-systems together remains 12 kg. Now, communication on the weights of the sub-systems is required.

The first strategy is the simplest one. One network of attributes is split into two independent networks, see Figure 3.6a. The sub-systems can be designed separately. The second strategy is more complex. One network is split into two dependent networks. The networks are related through the originating network, see Figure 3.6b. The choice between the two strategies will show to be important for the speed of the design process, the quality of the object design and the amount of communication required in the design process. The sections on parallel and sequential design and top-down and bottom-up design will deal with this subject.

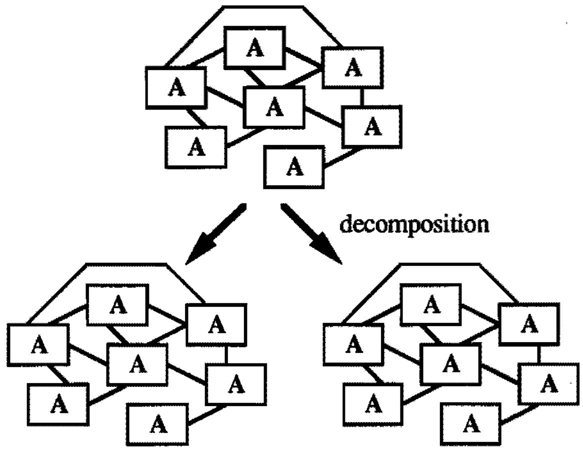


Figure 3.6a. Independent networks after decomposition.

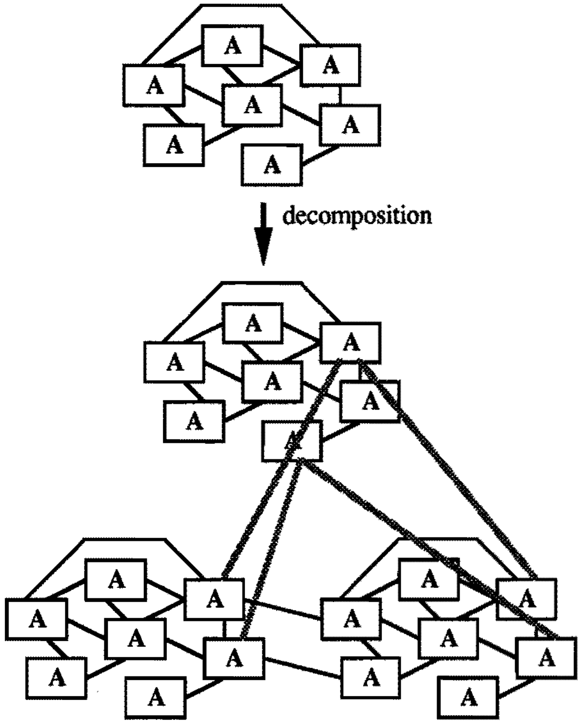


Figure 3.6b. Dependent networks after decomposition.

The design process of a sub-system evolves similarly to the design process discussed earlier. An objective definition phase can be identified. The rest of the design process can also be divided into phases.

Composition

After the discussion on the decomposition operation, the composition operation will be treated. Composition is the clustering of a set of sub-systems into one system. Composition, therefore, is the opposite of decomposition. In a decomposition action, a system is divided into two or more sub-systems, whereas in a composition action, two or more sub-systems are clustered in one (sub-) system. The mechanism for setting the attributes of the newly defined sub-system after a composition action is basically the same as described above for decomposition. The sub-system will have interaction with other systems in its environment. These IES's will set the attributes in the same way as earlier described for the objective definition.

For decomposition two different strategies are possible. Attributes can be designed individually or collectively. For composition, no such choice is possible. The resulting system is a result of the original sub-systems. Different problems, however, arise. The values of the original sub-systems can be conflicting. The value of this attribute for the resulting system needs negotiation. Figure 3.7 shows the clustering of two networks of attribute into one. A small example will illustrate composition.

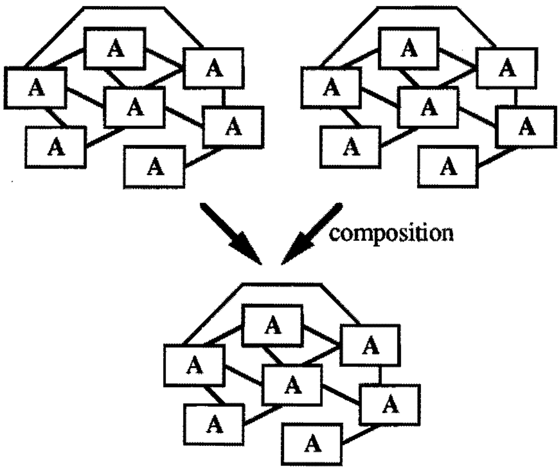


Figure 3.7. The composition action.

A manipulator needs to be designed. Early in the design process, the designer decides that the manipulator should consist of a translator and a rotator (decomposition). Later, he decides that both sub-systems should be integrated into one system (composition). Figure 3.8 illustrates this design process. Analysis of the translator has revealed that the material should be steel, for reasons of strength and cost. Analysis of the rotator has revealed that the material should be aluminium, for reasons of weight and cost. Material choice for the trans-rotator should be reconsidered. Steel, aluminium or even another material can result from this analysis.

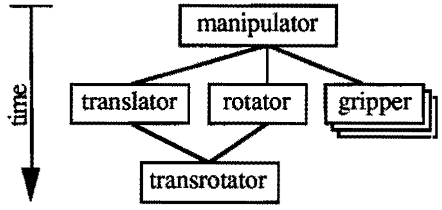


Figure 3.8. The design process of a manipulator.

The composition example illustrated composition as an iteration, rectifying decomposition by the composition action. Composition, however, is not always a rectification. An example will illustrate this. After several decomposition actions, 125 sub-systems result. Three times each (sub-) system has been divided into five sub-systems. Assume that two sub-systems perform the same function. The designer can then decide to use only one subsystem (composition). 124 sub-systems remain. This example is no iteration, but the negotiation problem is similar.

The interactions between sub-systems in industrial systems will be discussed in chapters 4 and 5. Attention will be given to the interactions between product and production system as well as manufacturing system and control system. Next, the parallel and sequential design of sub-systems will be defined and discussed.

3.4.2. Parallel and Sequential Design

After an object design has been decomposed, the sub-systems will be designed separately. Two different ways to design sub-systems will be discussed in this Section. Firstly, *parallel design* of sub-systems will be discussed. Sub-systems are designed in parallel if the sub-systems are designed simultaneously. Secondly, *sequential design* will be discussed. Two sub-systems are designed sequentially, if the design of one sub-system precedes the design of the other. In practice, a mixture of parallel and sequential design is possible. The design process of the second sub-system starts before that of the first sub-system ends.

Parallel Design

Firstly, parallel design will be discussed. Two sub-systems are designed in parallel if they are designed simultaneously. A minimum of two designers is employed. In this Section, the conditions for parallel design will be discussed, as well as its advantages and disadvantages.

Firstly, the conditions for parallel design will be discussed. Relations between sub-systems determine the applicability of parallel design. Parallel design requires sub-systems with no relations or sub-systems with pre-defined interrelated attributes. Alternatively, parallel design may be made possible by increasing the amount of communication between both design processes. This was discussed above as the two possible strategies following decomposition.

If no relations between sub-systems exist, the sub-systems can be designed in parallel, because no interaction is expected. If some related attributes are pre-defined, sub-systems can be designed in parallel, because interaction is defined at the start of the design process. Interfacing between both object designs is pre-defined.

If the designer opts for parallel design of sub-systems, relations between the sub-systems should be defined or communication between both design processes should be intensified. In practice, a mixture of both possibilities will be chosen. Then, some interfacing is pre-defined, whereas communication takes place on non-pre-defined attributes.

Secondly, some advantages and disadvantages will be treated. The apparent advantage of parallel design processes is the speed of the overall design process. Since activities are carried out simultaneously, the overall design process will be finished earlier. Another advantage of parallel design can be the standard interfacing, although, strictly, this is a prerequisite rather than a result.

Besides the advantages, some disadvantages can be mentioned. The first is that of possible sub-optimisation, because interfacing is defined at an early stage. This disadvantage is the result of the division into sub-systems. Defined relations between sub-systems can degrade the results of the design process. A small example will illustrate this. A certain product should have a maximum mass of 12 kg. Now, the designer decides that the product should consist of two sub-systems. He can pre-define the maximum masses of both sub-systems to be 6 kg (or for instance 4 and 8 kg respectively). Sub-optimal results are likely.

One possibility for improving possible sub-optimisation is increased communication. Designers of both design processes communicate on mutual influences. In the example above, maximum mass of both sub-systems would not be predetermined. Communication on both object designs would result in an overall mass of 12 kg. Communication in larger design processes, however, can become immense. There, some standardised interfacing is obligatory.

Sequential Design

After the discussion on parallel design of sub-systems, sequential design of sub-systems will be treated. Two sub-systems are designed sequentially, if one sub-system is designed before the other sub-system. In practice, a mixture of parallel and sequential design is possible. Then, the design process of the second sub-system starts before the end of the first sub-system's design process.

The conditions for sequential design will be discussed in this Section. Sequential design of sub-systems is always applicable. Because of the speed advantage of parallel design, sequential design is only done if parallel design is impossible or inexpedient.
Relations between sub-systems can be so strong, that one sub-system has to be designed before the other sub-system. The design process of the first should be (partially) finished, before the second design process can start. Chapter 4 will show an example of this in the relation between product design and manufacturing system design.

Secondly, the advantages and disadvantages of sequential engineering will be discussed. The apparent disadvantage of sequential design is the slow progress of the design process. Another possible disadvantage can result from the strong relations between the sub-systems. The designer of the first sub-system may not consider the relations appropriately. This will result in a sub-optimal second sub-system. A well-known example is the sequential design of product and manufacturing system. In the product design process, insufficient attention is sometimes given to the relations with the manufacturing system. The resulting manufacturing system is sub-optimal. This will be discussed more extensively in Chapter 4.

Advantages of sequential design processes are related to the disadvantages of parallel design processes. Interfacing does not need to be predetermined. Communication with other design processes requires less attention. The latter does not imply that relations between sub-systems need not to be considered. For this, communication with experts of other sub-systems is necessary.

In practice, parallel and sequential design are applied in a mixture. By doing so, the advantage of a quicker design process is combined with the advantages of sequential design, less communication and less interfacing definitions. Chapter 4 will go into this matter more deeply concerning the design of industrial systems. Next, top-down and bottom-up design will be defined and discussed.

3.4.3. Top-down and Bottom-up Design

The division of the object design can be done using a *top-down* or a *bottom-up* approach. Following, both top-down and bottom-up design processes are discussed. It will be shown that actual design processes contain a mixture of both extremes. Interactions between sub-systems are discussed in the next Section. The relation of top-down and bottom-up design with parallel and sequential design will be discussed. The difference between hierarchical modelling and hierarchical (top-down and bottom-up) design will also be discussed.

Top-down Design

A design process in which the object design is divided into ever smaller individually designed sub-systems is called a top-down design process. Figure 3.9 illustrates this. The design process starts with an abstract object design. This is divided into several sub-systems. These sub-systems are, again, divided into more sub-systems. This procedure continues until, finally, there is a set of sub-systems designed and realised individually. In other words, only decomposition is applied. Composition does not take place.

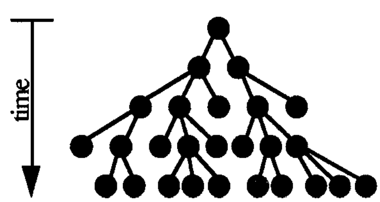


Figure 3.9. An example of a top-down design process.

If the different sub-systems are designed in parallel and not sequentially, top-down design will result in a quickly evolving design process. Since this is the most extreme form of parallelisation, top-down design can result in the quickest possible design process. The disadvantage of a sub-optimal object design is, as previously mentioned, apparent. Since the overview of the design process is minimal, top-down design can result in the worst object design. Consequently, top-down design can result in the quickest possible design process but the danger of sub-optimisation is great.

Bottom-up Design

A design process in which the object design is first divided into elementary sub-systems, that are clustered into sub-systems to be designed individually, is called a bottom-up design process. Figure 3.10 illustrates this. Again, the design process starts with an abstract object design. This is divided into several sub-systems. These sub-systems are, again, divided into sub-systems. This procedure continues until, finally, there is a set of elementary sub-systems. These elementary sub-systems are then clustered in an optimal way, before being designed and realised individually. In other words, first, decomposition takes place to the elementary level. Then, composition is applied.

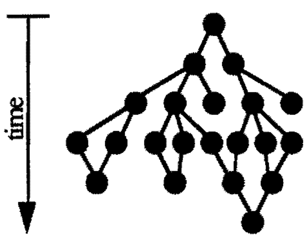


Figure 3.10. An example of the bottom-up design process.

Neither parallel nor sequential design can be applied in bottom-up design. The designer always perceives the entire object design. Therefore, bottom-up design will result in a slowly evolving design process. The overview of the design process is maximised, because the elementary sub-systems are clustered optimally. Bottom-up design can result in the best object design. Consequently, bottom-up design can result in an optimal object design, but the design process will evolve slowly.

The term bottom-up design is often applied in redesign processes. An existing set of physical means is structured in a different way. The structure is redesigned by first making groups of means, then clustering these groups, etc. This procedure is called ***bottom-up redesign.*** Bottom-up redesign is similar to bottom-up design as defined above regarding the composition part. In bottom-up redesign, the decomposition part has been done in the design process before the iteration (redesign). This decomposition resulted in a set of means, that are reclustered in the bottom-up redesign. To distinguish between both types of bottom-design, the term ***configuration design*** is preferred for bottom-up redesign. Existing or modular elements are (re-) configured into a new or improved object design.

Top-down and Bottom-up Design in Practice

Top-down and bottom-up design have been discussed in the previous sections. It is shown that top-down design can result in the quickest possible design process and that bottom-up design can result in the best possible object design. In reality, there will often be a competition between both goals: a good design in a reasonable amount of time.

Top-down design does not allow the designer to iterate on a division into sub-systems. This implies that designers should always make optimal choices. Bottom-up design does not allow the designer to cluster before he has reached all the elementary functions. This can easily lead to an unmanageable amount of sub-systems.

Real design processes will consist of a mixture of decomposition and composition. Figure 3.11 shows an example. Real design processes will be somewhere in between the extremes top-down and bottom-up design. The optimal mixture of top-down and bottom-up design is dependent on the goals set to the design process. Emphasis on an optimal object design should result in a more bottom-up-like variant; emphasis on speed should result in a more top-down-like variant.

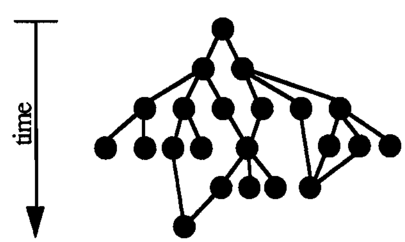


Figure 3.11. A real design process with decomposition and composition.

The third axis of the design cube has been treated in this Section. Decomposition and composition have been discussed. Parallel and sequential design of sub-systems have been treated. Top-down and bottom-up design have been defined and discussed. The actions necessary to divide the object design into subsystems are decomposition and composition. Top-down design, bottom-up design and mixtures of both, are related to the sequence of decomposition and composition. Parallel design, sequential design and mixtures of both are related to the organisation of the design process.

The first and the second axis of the design cube have been treated earlier. The concepts of attributes and level of design abstraction have been discussed. All concepts treated in this Chapter can easily lead to confusion, and this will be addressed in the following section.

3.5. Review

The third axis of the design cube has been discussed in the previous Section, and before that the abstraction axis and the attributes axis. The discussions produced a number of concepts that are closely related. Confusion, therefore, is possible, which could lead to misinterpretations. In this section, the nature and consequences of such confusion will be examined.

Two different abstraction mechanisms have been discussed. Firstly, design abstraction has been treated. The knowledge on the object to be designed gradually grows more concrete in the design process. Knowledge is abstract in the beginning of the design process. Knowledge is concrete at the end of the design process. Secondly, modelling abstraction has been treated. A concrete system or object design can be modelled; a representation can be made. Not all of the knowledge on the system or object design is incorporated in the model. Modelling abstraction is used.

A complicating factor in modelling abstraction is the concept of model-hierarchy. Model-hierarchy is applied if the model is too complex to be understood in one view. Different levels of modelling abstraction can then be applied in one model. Zooming-in on an abstract model shows the more concrete model of that part. An example of model-hierarchy is the use of parameters in formulas. Figure 3.12 shows an example, the formula of Navier-Stokes [Vossers, 1986]. The complexity of the first formula is greater than the complexity of the second formula.

$$\frac{\omega L}{v}.\frac{\partial \underline{v}}{\partial t}+\underline{v},grad\underline{v}=-gradp+\frac{gL}{v^2}.\underline{g}+\frac{\eta}{\rho vL}.\nabla^2.\underline{v}$$

with:

$$Sr=\frac{\omega L}{v},$$

$$Fr=\frac{v^2}{gL},$$

$$\mathrm{Re}=\frac{\rho vL}{\eta},$$

$$gives: Sr\frac{\partial \underline{v}}{\partial t}+\underline{v},grad\underline{v}=-gradp+\frac{1}{Fr}.\underline{g}+\frac{1}{\mathrm{Re}}.\nabla^2.\underline{v}$$

Figure 3.12. Model-hierarchy in formulas.

Many (computerised) modelling techniques apply some form of model-hierarchy. Modelling techniques that are used during the design process should support both zooming-in and zooming-out functions, because both decomposition and composition is possible.

Another possible confusion can arise by misinterpreting design abstraction. It has been stated that the design process by definition goes from abstract to concrete. Knowledge on the object design gradually becomes more concrete during the design process. Sometimes, the design process is claimed to be a top-down process. This, however, can be interpreted as that top-down design as defined in Section 3.4.3 is preferable to bottom-up design. Top-down design, in this case, is used with two different meanings. It has been shown that both top-down and bottom-up design can be applied. The designer should choose the strategy appropriate to a specific design process.

Finally, confusion is possible concerning the different approaches and mechanisms in the division of the object design into sub-systems. Two mechanisms have been discussed for the division of the object design: decomposition and composition. With these two mechanisms the designer decides on an optimal division of the object design.
The sole use of decomposition leads to top-down design. Advantages and disadvantages of this extreme approach to the design process have been discussed. Bottom-up design is defined as a process where, after the decomposition of the object design into elementary sub-systems, composition takes place. Advantages and disadvantages of this extreme

approach have also been discussed. Decomposition and composition are used in a more mixed way in reality. Therefore, designers in real design processes will use a mixture of top-down and bottom-up design.
If the design is organisationally split after decomposition, one can speak of parallel design. The design processes of the various sub-systems are performed independently. If the sub-systems are decomposed, but designed sequentially, one can speak of sequential design.

Different concepts concerning the structuring of the design process have been discussed in this Chapter, with special attention to the possible confusion of the concepts. Next, a general method will be presented for the structuring of design processes. This method will be used in the next Chapter to structure the industrial system design process.

3.6. A Structuring Method

The objective of this Chapter was to formulate a method for the structuring of design processes. For this, a number of concepts have been defined and discussed. These concepts will be used in this Section to formulate a method for the structuring of design processes.

The structuring of a design process can be seen as the division of the design cube. Three axes need examination: attributes, design abstraction and sub-systems. The sequence of the axes to be studied can be prescribed. The design process starts with the definition of the objective. Then, the rest of the design process needs structuring. Firstly, a division into basic sub-systems needs to be made. Next, phases need to be introduced for the design processes of the various sub-systems. Thirdly, the attributes need to be studied. This should reveal relevant attributes for each design phase of every sub-system. Methods and techniques dealing with the relevant attributes can be selected or developed to fill in the structure. The designer can be supported in all four steps of the decision cycle: (1) analysis, (2) synthesis, (3) evaluation, (4) decision.

This sequence follows from the fact that to know which methods to apply, the place in the design process and the relevant attributes need to be known. Phasing of the design process, therefore, should be done before the determination of relevant attributes and selection or development of methods. Phasing of the design process can only be done after the determination of the basic sub-systems, because each basic sub-system requires different treatment.

Procedure for the structuring of design processes
1. Formalisation of objective definition
2. Identification of basic sub-systems
3. Phasing of the design processes of basic sub-systems
4. Determination of relevant attributes
5. Selection or development of methods and techniques for: - analysis - synthesis - evaluation - decision

Figure 3.13. General procedure for the structuring of design processes.

The global structuring procedure has been presented. Figure 3.13 shows the steps in the procedure. Now, the various steps will be discussed in detail.
The first step is concerned with the definition of the objective. This part of the design process consists of all design decisions that are taken by systems outside the system to be designed. The second step is concerned with the division into basic sub-systems. Attention should be given to the relations between the sub-systems. If they are too strong, division in the structure is not sensible. Chapter 4 will show examples of this. To decompose the object design in an appropriate way, basic sub-systems should be chosen such that they can be designed in parallel or sequential way. If the sub-systems should always be considered together, division should be avoided. By selecting basic sub-systems in this way, sub-systems that should be considered together are treated similarly. Phasing is similar and design methods are selected that take care of these strong relations.

The result of the second step is a number of basic sub-systems that can be designed organisationally separate. Phases can be introduced to structure the design processes of the various basic subsystems. Different levels of design abstraction are introduced. The number of phases depends on the complexity of the sub-system, the experience of the designer, etc. This has been discussed in Section 3.3. The sub-system can also be designed in a single phase. Different numbers of phases can be used for different sub-systems. The number of phases can be increased or decreased as the situation requires.

The result of the third step is a number of phases for the various basic sub-systems. Next, the attributes are studied. Relevant attributes are derived for each phase of every basic subsystem. At this point, design documents can be defined. The design documents are the results of an individual phase. The level of design abstraction of the attributes needs to be defined for every phase. The design abstraction of the sub-system's structure can also be defined. By doing so, the phases as well as the design documents are defined.

The result of the fourth step is a set of design documents for each phase of every sub-system. The design process has been structured. This structure can be filled in with methods and techniques that support decision-making. All four steps of the decision cycle should be supported. The methods and techniques can be selected or developed taking account of the relevant attributes that have been collected in the fourth step. The procedure described in this Section will be used in the next Chapter to structure the design process of industrial systems.

This Chapter will be concluded with a discussion on the structuring of design processes. The feasibility and usefulness of structuring design processes will be treated. After this, conclusions concerning the structuring of design processes will be drawn in Section 3.8.

3.7. Discussion

The structuring of design processes has been treated in this Chapter. It presented a procedure that can be used in the structuring of design processes. The benefit of structured design for the quality of the design process and the object design is often discussed in the design community. Advocates point out the significant successes that have been achieved deploying structured design. Opponents refer to design problems in which structured design has proved to be frustrating. This Chapter has presented a procedure to structure design processes. The concepts that were defined and discussed will be used to clarify some of this discussion.

The design of an object can be modelled as moving from the upper plane in the design cube to the lower plane. The knowledge on the object to be designed is abstract in the beginning of the design process, becoming concrete at the end. Design can be seen as the making of design decisions to move from abstract to concrete.

The standard procedure, visualised in Figure 3.13, shows that the three axes of the design cube should be divided in an appropriate way to structure decision-making. The structuring process, therefore, should be performed for every individual design problem. Some design problems may require the division into several basic sub-systems. In another design problem, the designer may not be able to define basic-sub-systems. The introduction of phases may be useful for some design problems, useless for others.

The attributes axis can also be divided. The designer can subsequently deal with sub-sets of all attributes. Research on specific design problems should reveal the significance of various (sub-sets of) attributes. Methods and techniques then can be developed that can be used to support decision making. Cognitive research should investigate the way designers deal with the division of the attributes axis.

The appropriate structuring of the design process is dependent on the individual situation. Innovative design, for instance, may require a different treatment than redesign. The design process of an innovative product may not be structured at all. The reason for this can be that the designer moves from abstract to concrete in a chaotic rather than an ordered way. An idea jumps to the designer's mind. This idea is concretised and evaluated in a split-second. Iteration takes place and the initial design is altered. The design process can still be seen as moving from the upper plane in the design cube to the lower plane. The designer's path, however, may be far from linear. Structuring the design abstraction axis then may not be useful, because the levels of design abstraction need to be crossed many times.

The redesign of an existing product, however, can indeed benefit from a more structured approach. Basic sub-systems can be identified. The introduction of phases in the design process can help the designer to structure his decision-making on the various levels of design abstraction. Design methods and techniques can be selected to support the designer in his decision-making process. Redesign is an iteration on previously made design decisions. In a redesign project, structured design can be used to investigate all previously made design decisions. Again, the decision cycle can be used. The synthesis step of the decision cycle is then skipped. If in the decision step, however, the designer decides to reconsider the design decision, all four steps, including synthesis will be addressed. By doing so, the designer is sure not to forget any important design decision.

All this implies that more research is necessary on how designers make design decisions. The hypothesis on the relation between the degree of innovation and the level of structuring should be investigated. The relationship of individual designer abilities with the level of structuring should be studied. The general guidelines for the structuring of design processes that have been presented in this Chapter can then be made more specific.

Conclusions concerning the structuring of design processes will be presented in the next Section.

3.8. Conclusion

The different concepts used in the structuring of design processes have been discussed in this Chapter. A study of system theory revealed that an extra concept was required. This led to the introduction of the design cube. The three axes of the design cube are attributes, (sub-) systems and design abstraction. The design cube models the object design in the design process. A plane perpendicular to the design abstraction axis contains a model of the object design at a certain level of design abstraction. The design process, therefore, can be seen as the process of moving from the upper plane in the design cube to the lower plane. Decision making in the design process can be seen as the filling in of a network of attributes. The human decision making process has been modelled as cycle of four steps. Firstly, the initial situation is analysed (1). The actual design decision is made in the synthesis step (2). There, the network of attributes is filled in. The new object design is evaluated in the evaluation step (3). Acceptance or rejection of the design decision takes place in the decision step (4). A structured design process can be seen as a structured series of decision cycles. Methods and techniques should, therefore, be developed for all four steps in the decision cycle.

The three axes of the design cube have been discussed separately. The structuring of the design process concerning these three aspects is dealt with. Confusion of the various concepts defined in this Chapter can arise. Clear distinction between the various concepts will avoid this confusion.

More cognitive psychological research is required to model the thought processes of the designer in the design process. This research may reveal how the designer comes from the upper plane of the design cube to the lower plane. It should show the dependency on individual designers, experience of the designer, knowledge on the design problem, complexity of the object design, the degree of innovation of the object design, etc. Until then, no detailed information can be given on how designers should go through the design cube, or in other words structure the design process. In this chapter, general guidelines are given for the structuring of design processes. This has resulted in a procedure that can be used for every individual design process. With the theory on the structuring of design processes presented in this Chapter, the first research objective stated for the research project has been achieved.

The general guidelines to the structuring of the design process given in this Chapter will be used in the next Chapter to achieve the second research objective. The development of a structured design method consists of five steps. These steps will be executed for the industrial system design process in the next Chapter. A standard structure will be proposed that can be adapted in individual cases. Standard documents will be introduced. The fifth step will only briefly be treated. Methods and techniques supporting the four steps of the decision cycle will be discussed for the various design problems in industrial system design. The standard structure will be tested empirically in Chapter 5, and will be illustrated with an example in Chapter 6.

Chapter 4

Structuring the Industrial System Design Process

The design of industrial systems is often done with the aid of only intuition and experience. This unstructured approach to the design process may lead to unsatisfactory object designs. A more systematic approach to the design process, however, can help to improve the decision-making process. A designer is guided through the design process and pointed to relevant aspects. This can be achieved by structuring the design process.

In the previous Chapter, the structuring of design processes has been discussed. Chapter 3 has presented the general concepts of the structuring of design processes. For this, the design cube has been presented. The three axes of the design axes are sub-systems, design abstraction and attributes. Now, design can be seen as the process of moving from the upper plane in the design cube to the lower plane.

The making of design decisions during the design process can be modelled by the general decision cycle, discussed in Chapter 2. The continuous application of the four steps – analysis, synthesis, evaluation and decision – gradually make the object design more concrete. The network of attributes is filled in. The structuring of decision-making in the industrial system design process is treated in this Chapter. This will reveal which decisions to take where and when, but not how.

Studying and dividing the three axes of the design cube will lead to a standard structure of the design process of industrial systems. It has been shown that the use of a rigid structure has disadvantages. Designers will not be able to follow rigid prescribed structures. Every individual design process should be structured according to the system to be designed, and the desires and limitations of the individual designer. The standard structure, therefore, should be adapted to the individual situation.

The rest of this Chapter is organised as follows. The structuring of the design cube will be used in this Chapter to structure the design process of industrial systems. Firstly, therefore, the definition of the objective of an industrial system will be treated. Secondly, the division of the industrial system into basic sub-systems is discussed. Thirdly, the phasing of the design processes of the resulting basic sub-systems is discussed. Fourthly, the attributes are discussed per sub-system and design phase. Reference will be made to existing methods and techniques that support the four steps in the decision cycle in each design phase. This Section is necessarily only a concise summary of the existing bulk of methods and techniques. Besides this, the foundations of new methods for the manufacturing system design process will be discussed. The Chapter will conclude with a review of the structured design process.

4.1. Objective Definition

Each design process starts with the objective definition. In the objective definition phase, Interested External Systems (IES's) give values to attributes, whereas in the rest of the design process, it is the designer who gives values to the attributes. The introduction of an objective definition phase, therefore, is justified. A clear distinction in time between the objective definition and the rest of the design process is often not possible. IES's will change or concretise the values of the attributes. This means that in practice, some of the objective definition is done during the rest of the design process.

A three-step procedure has been proposed in Chapter 3. Figure 3.5 illustrated this. The IES's are identified in the first step. The attributes that the IES's take interest in are identified and set in the second step. There, hard constraints are set, after which it is possible to determine the validity of an object design. If an object design does not violate constraints posed by the IES's, it is called valid. Still, the best object design cannot be determined. In the third step, therefore, the attributes are weighed. There, soft constraints are set and weighed. Now, it is possible to compare valid object designs, and the best object design can be chosen.

The three-step procedure will be used in this Section. For this, a general industrial system is used. The results presented in this Section, therefore, are theoretical and should be tailored to the individual situation. Firstly, the IES's will be identified. Secondly, the attributes the IES's in general take interest in are identified. Thirdly, the attributes are weighed. Finally, a review on the Section is given.

4.1.1. Identification of the Interested External Systems (IES's)

The first step in the procedure for objective definition is the identification of the Interested External Systems (IES's). The IES's are the systems in the environment of the system to be designed that take interest in that system. The IES's of a general industrial system will be identified in this Section.

For this, an industrial system is seen as the collection of products and a production system. A production system is defined as a collection of human and physical resources, producing products for which in return it receives a compensation. Using this definition of a production system, the IES's of the industrial system can be identified.

In the definition of a production system, two basic flows are considered. The first flow is the flow of matter (raw material, semi-manufactures and products). The second flow is the flow of energy (money), compensating the first flow. These two basic flows are maintained and synchronised by a third flow, the flow of information [Arentsen, 1989]. These flows are the basic interactions of the production system with its environment. Some IES's, therefore, can be derived from the flow of matter and energy. The flow of information always maintains another flow. Therefore, studying the flow of information will not produce extra IES's.

Each flow has a source – a supplier – and a destination – a consumer. Studying the flow of matter leads to the identification of two IES's. The *matter suppliers* supply all raw material and semi-manufactures to the production system. The *matter consumers*, customers consume all products coming from the production system. Contrary to this flow of matter, is the flow of money. No extra IES's, therefore, will be identified by investigating this flow of energy. Temporarily, however, the production system may need extra energy input. The production systems may want to overcome fluctuations in the financial balance or may want to invest in new equipment. This leads to the introduction of a third IES: the *energy suppliers* (financiers). Studying this extra energy flow reveals that the energy consumers are identical to the energy suppliers.

The definition of a production system assumes the presence of human and physical resources. Three IES's follow from this statement. The production system interacts with its environment through the flow of equipment. The human resources come from the *labour market*. The physical part is supplied by the (physical) *equipment suppliers*. If the physical equipment has become technically or economically obsolete, it is transferred to the (physical) *equipment consumers* (demolition firms, etc.).

Finally, all other interactions are clustered in an extra IES: *government*. Government interacts with the production system, representing general interest. Seven IES's have now been identified: (1) matter suppliers, (2) matter consumers (customers), (3) energy suppliers (financiers), (4) labour market, (5) equipment suppliers, (6) equipment consumers (demolition firms) and (7) government. This is illustrated in Figure 4.1.

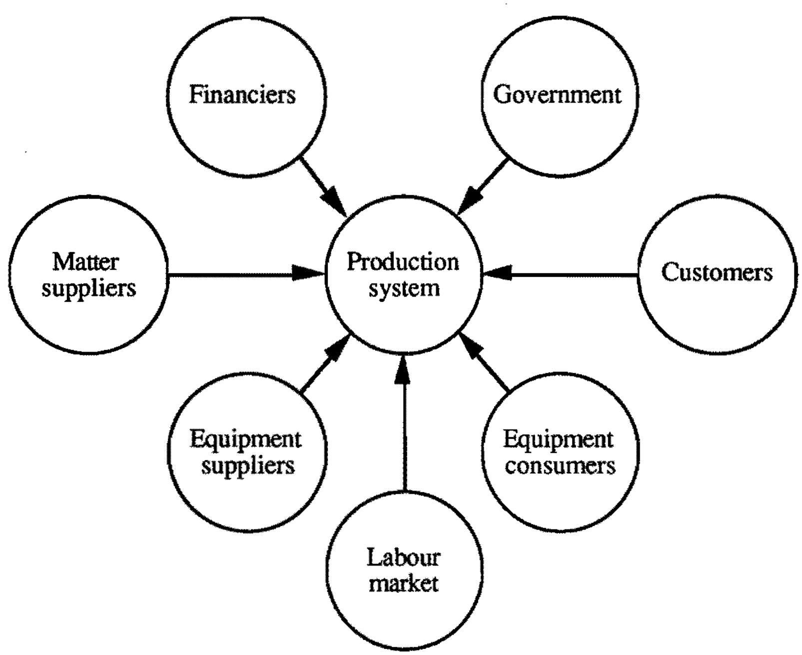


Figure 4.1. Interested External Systems of a general production system.

A more detailed view can be achieved. The labour market can be divided into blue and white collar sections. Equipment suppliers can be divided into machinery suppliers, tool suppliers, transportation system suppliers, computer hardware and software suppliers. Here, an abstract view is maintained for purposes of generalisation.

The identification of the IES's for the production system also led to the identification of the IES's for the products. In doing so, the objective of the industrial system can be defined. Above, the IES of the products are collected in the matter consumers. A more detailed view may be necessary to take account of wishes and demands of the different customers. Market segmentation is studied to identify the different market sectors. The different market sectors will reveal different IES's for the products. Here, customers are seen as one IES.

4.1.2. Identification of the Attributes

Seven IES's have been identified in the previous Section. These are all concerned with the industrial system in one way or another. All IES's take interest in certain attributes of the system to be designed. The attributes are identified in the second step of the objective definition.

Several aspects of the interactions of the various IES's with the industrial system can be studied. Besides the interaction content, different aspects will prove to be relevant for the various parties. Possible attributes of the interaction that can be identified are the interaction content and the time-constraints on the interaction. Table 4.1 shows the result of this exercise.

Table 4.1. Objective attributes of a general industrial system.

Interested External System	Primary flow	Secondary flow	Tertiary flow
Matter suppliers	**Matter** (material) content: functionality quality amount time: delivery time	**Energy** (money) content: amount time: delivery time	**Information** (orders and invoices) content: protocol time: delivery time
Matter customers	**Matter** (products) content: functionality quality amount time: delivery time	**Energy** (money) content: amount time: delivery time	**Information** (orders and invoices) content: protocol time: delivery time
Equipment suppliers	**Equipment** content: functionality quality amount time: delivery time	**Energy** (money) content: amount time: delivery time	**Information** (orders and invoices) content: protocol time: delivery time
Equipment customers	**Equipment** content: state	**Energy** (money) content: amount time: delivery time	**Information**
Labour market	**Personnel** content: education level working conditions	**Energy** (money) content: amount time: delivery time	**Information**
Financiers	**Energy** (money) content: amount conditions time: delivery time	**Energy** (money) content: amount time: delivery time	**Information** content: protocol time: delivery time
Government	**Information** content: possibilities laws	**Energy** (money) content: tax amounts time: delivery time	**Information**

4.1.3. Weighing of the Attributes

The validity of an object design can be determined after the identification of all relevant attributes. If values of these attributes for a specific object design are within the boundaries set in the first two steps of the objective definition, the object design is called valid. It is, however, impossible to compare valid designs. Attributes need to be weighed by the designer and his client.

The weighing of the attributes is an inherently subjective procedure. Techniques have been developed that decrease subjectivity. German Wertanalyse [VDI, 1976] and Anglo-Saxon Value-analysis [ASTME, 1967] can be used to weigh the attributes. Proper weighing of the attributes is important, because different objectives will result in totally different object designs. The example of the hen-house in Chapter 3 has illustrated this. An industrial example will be shown in Chapter 6.

4.1.4. Conclusion

A method for the definition of the objective has been proposed in this Section. The method first identifies the IES's, then identifies the relevant attributes the IES's take interest in and, finally, weighs the attributes. More important than following the method, is the understanding that objective attributes should originate outside the system to be designed. Since the object design has no own preferences, objective attributes cannot originate from within the object design. If preferences originate from the designer, the designer is obviously an Interested External System. The designer interacts with the system and takes interest in certain attributes. Often, this is not the case.

This implies that many attributes are not likely to become objective attributes, because no IES's will be directly interested in them. In literature on industrial systems, capacity utilisation is often mentioned as an objective attribute. The reason for this is that the production manager is judged on his ability to achieve high capacity utilisation, but no IES can be found that is interested in this attribute. Optimisation of the industrial system towards this attribute, therefore, will not lead to the true optimum. Table 4.2 shows some objective attributes that originate from IES's, and some that are not likely to originate outside the industrial system.

Table 4.2. Examples of true and false objective attributes in industrial system design.

True objective attributes	False objective attributes
customers	lead time
delivery time	degree of capacity utilisation
product reliability	market share
product price	work in progress
financiers	failure rate
return on investment	
labour market	
salary	
working conditions	
government	
emission levels	

The false objective attributes must be treated with care. Since these attributes often have strong relations with true objective attributes, they can be used. Optimisation towards these attributes, however, will possibly lead to an unsatisfactory industrial system.

4.2. Sub-systems of Industrial Systems

After the definition of the objective for the industrial system, the rest of the design process starts. The second step in the structuring method prescribes the division of the system into basic sub-systems. This will be discussed in this Section. The next steps of the structuring method will be treated in subsequent sections.

The theory in Section 3.4 on the division into sub-systems will be used in this Section. Here, the division of the industrial system into sub-systems will be discussed. Firstly, a division into basic sub-systems will be proposed, and following that, the different basic sub-systems will be discussed separately.

4.2.1. Product and Production System

In this dissertation, an industrial system is seen as the collection of products and the production system that produces those products. In other words, products and production system are sub-systems of the industrial system. The design of the products and the production system are strongly related. Figure 4.2 shows part of the two interrelated networks of attributes.

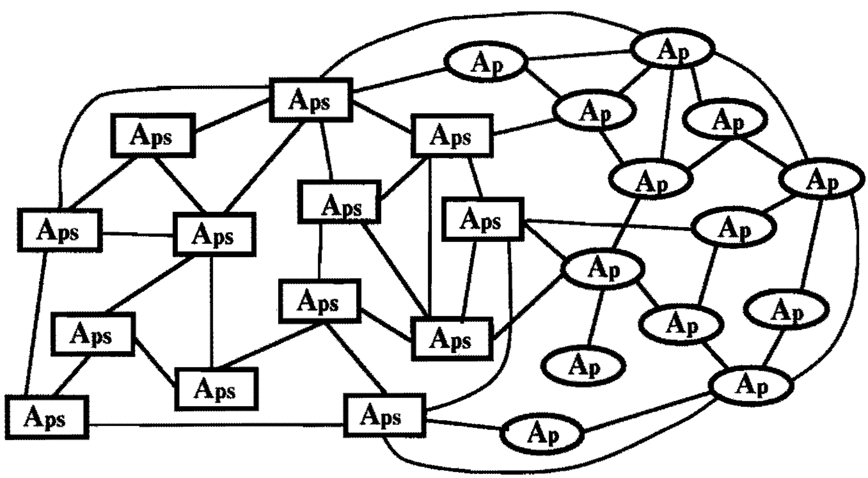


Figure 4.2. Interrelated attributes of products (A_p) and production system (A_{ps}).

Design of products and production system are traditionally performed sequentially. The fact that they are strongly interrelated demands for a more concurrent approach. Three kinds of relation can be distinguished in Figure 4.2. Firstly, the relations between attributes of the product: the product-to-product relations. Secondly, the relations between attributes of the production system: the production system-to-production system relations. Thirdly, the relation between attributes of the product and attributes of the production system: the product-to-production system relations. Methods and techniques supporting decision-making concerning the various types of relations have been discussed in Chapter 2.

4.2.2. Sub-systems of the Product

The product can be divided into sub-systems. The diversity of products makes it difficult to advocate a standard division into sub-systems. For some classes of products, standard divisions may be suitable. In most cases, however, the division into sub-systems will be done in the individual design process. Consequently, no standard division will be advocated here.

The division into sub-systems of products, however, is relevant for the production systems design. The structure of the product will partly determine the structure of the manufacturing system. The structure and consequently the division into sub-systems, therefore, needs consideration. This subject will be discussed in Sections 4.3.2 and 4.4.2 in more detail.

Ulrich and Tung discuss the fundamentals of product modularity. They discuss the advantages and disadvantages of modular product design. Advantages are component economies of scale, product change, product variety, order lead-time, decoupling of tasks, design and production focus, component verification and testing, differential consumption, facilitation of production, installation and use and, finally, ease of product diagnosis, maintenance, repair and disposal. Besides the advantages, they observe potential disadvantages of modular product design: static product architecture, performance optimisation, ease of reverse engineering, increased unit variable costs and excessive product similarity [Ulrich, Tung, 1991].
A modularly designed product, for example, can result in a special kind of production system. The modules are made on stock and the products are assembled to order. High product flexibility is coupled to a relatively low cost production system. This production system could not be designed in this fashion without consideration during product design.

4.2.3. Sub-systems of the Production System

The industrial system has been divided into the sub-systems product and production system. The production system, in turn, will be divided into sub-systems. For this, three basic flows in an industrial system will be distinguished. These are the flow of matter, the flow of energy (money) and the flow of information [Arentsen, 1989]. These flows have also been used in the Section on objective definition.

Three sub-systems can be derived from these three basic flows. Firstly, the sub-system that maintains the flow of matter: the *manufacturing system*. Secondly, the sub-system that maintains the flow of energy: the *financial system*. Thirdly, the sub-system that maintains the flow of information: the *information system*.

The focus in this dissertation will be on the manufacturing system. The reason for this is that the unit operations, or primary processes, determine the performance of the production system. In addition, the control of the primary processes is given attention. Following that, the manufacturing system and information system will be discussed with regard to the division into sub-systems. The financial system will not be treated in this dissertation. After this, the phasing of the design process and the attributes will be treated per basic sub-system.

4.2.4. Sub-systems of the Manufacturing System

The manufacturing system can be divided into sub-systems in many ways. It is possible to divide the manufacturing system into a human and a non-human sub-system. This division can be justified, because a concrete manufacturing system does consist of a human and a non-human part. It is, however, a division on a low level of abstraction, saying nothing of their more abstract functionality. In early phases of the design process, this division will be of little help.

A distinction, therefore, needs to be made in the level of abstraction at which a certain division should be used. The division mentioned above will be used at lower levels of abstraction. Other divisions can be used at higher levels of abstraction. Division on a high level of abstraction focuses on functionality more than on form.

Several sub-systems divisions have been proposed in literature. Kienzle, Ehrlenspiel and DIN 8580 propose different classification of processes [Van De Ven, 1989]. Smit proposes a division into 10 operations [1992]. Figure 4.3 shows the operations proposed by Smit.

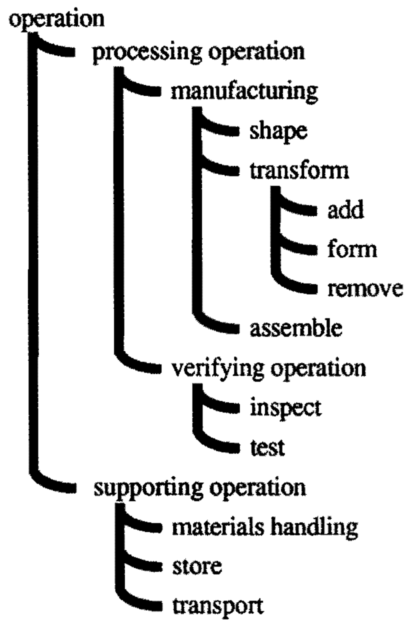


Figure 4.3. Basic operations in a manufacturing system [Smit, 1992].

Any of the proposals mentioned above can be used in the division of the manufacturing system into sub-systems. All sub-systems, however, are strongly related. The sequential design of the sub-system, therefore, will inevitably lead to sub-optimal manufacturing systems. This understanding has led to the development of the logistics speciality.

4.2.5. Sub-systems of the Information System

The information system also can be divided into sub-systems. An administrative sub-system can be distinguished that manages information flows concerning personnel, finance, management, etc. This administrative sub-system will not be studied here. The sub-system that is studied here, is the part that directly controls the matter flow. The ordering of matter from the matter suppliers, the control of the equipment and processing of customer orders is part of the information system in question. This part is called *matter control system* or shorter *control system*. Another part of the information system is the part that controls the flow of energy. This part is called the *financial control system*.

The control system, controlling the flow of matter through the industrial system, consists of many sub-systems. In the literature on control system design, many standard control architectures have been proposed. In most cases, a fixed number of system-hierarchical levels is used. Implementation of these architectures, in most cases, requires adaptation to the individual situation. Standard architectures are proposed by, for instance, the National Bureau of Standards [Simpson et al., 1982], Beukeboom [1989] and Williams [1985].

In addition to these standard architectures, more flexible variants exist. Smit proposes a standard architecture where every system-hierarchical level is similar and where standard controllers can be used on all levels [1992]. This architecture is more flexible than the architecture mentioned before.

The use of standard controllers is another way to divide the control system into sub-systems. Numerous standard controllers have been proposed in the literature, including those of Albus [1981] and Davis [1992].

The division of the control system, i.e. that part of the information system that controls the flow of matter, can be done in several ways. Standard architecture, standard hierarchical levels or standard controllers can be used. Here, no preference will be given. Consequently, no division of the control system into sub-systems will be used in this dissertation. A method for the division into sub-systems will be given in Section 4.3.3.

Since the control system is the only part of the information system that is studied in this dissertation, only the control system will be treated from hereon. Other parts of the information system, however, should also be considered in the design of industrial systems. Here, the flow of matter (the product sub-system), the system that maintains the flow of matter (the manufacturing system sub-system) and the system that controls the flow of matter (the control system sub-system) will be taken into account.

The division of the information system into sub-systems has been discussed in this Section. Two basic sub-systems have been distinguished: the (matter) control system and the financial control system.

4.2.6. Parallel and Sequential Design of Sub-systems in an Industrial System

Above, the basic sub-systems in an industrial system have been identified. Figure 4.4 shows the five basic sub-systems in an industrial system.
The parallel and sequential design of sub-systems has been discussed in Section 3.4.2. That discussion revealed that parallel design of sub-systems is possible if no relations between the sub-systems exist, if interfacing is fully defined or if extensive communication on the relations takes place. Here, the parallel and sequential design of sub-systems in industrial systems will be discussed. Figure 4.4 illustrates the various basic sub-systems in an industrial system.

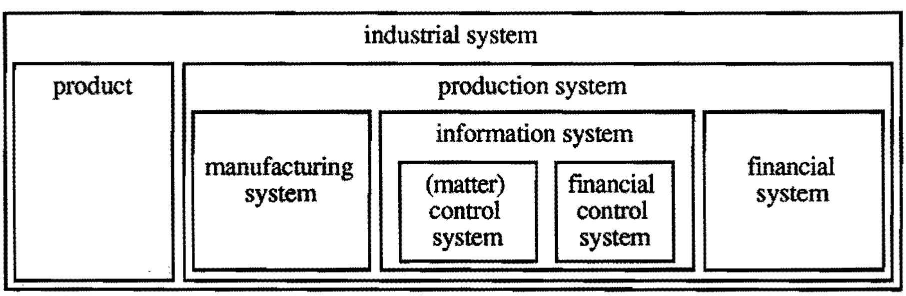


Figure 4.4. The basic sub-systems of an industrial system.

The criterion of no relations between sub-systems is not valid in industrial system design. Relations between product, manufacturing system, information system and financial system design are numerous. Relations between product and production system can be pre-defined. This requires standards in both product and production system design. Sub-optimal solutions can easily result. Extensive communication is the third possibility to obtain parallel design. The extra communication can cancel out any gain in speed, resulting from the parallel design.

So, parallel design of product, manufacturing system, information system and financial system is possible only at the expense of standardisation and extra communication. Sub-optimal object designs and a relatively slow design process may result. Therefore, a more sequential approach is most often applied. Figure 4.5a, b and c show the parallel, sequential and mixed design of basic sub-systems.

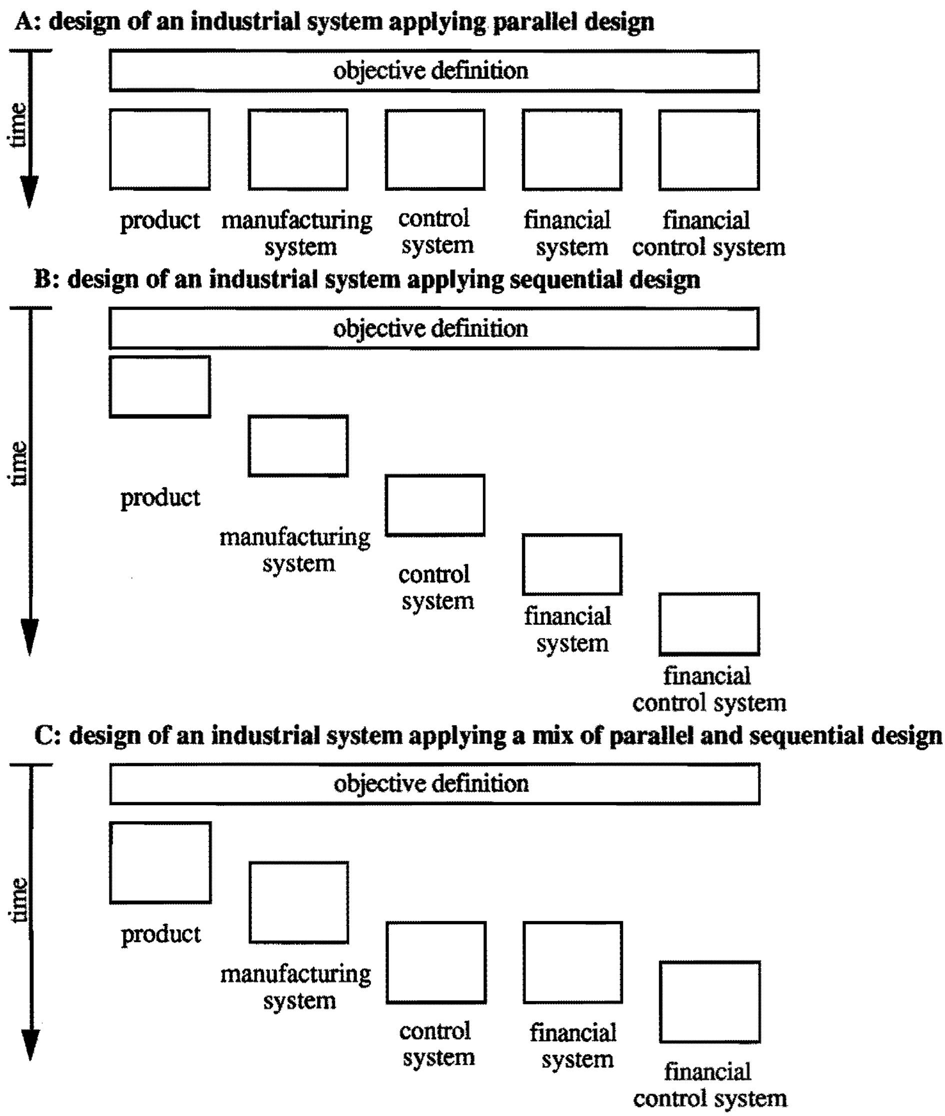


Figure 4.5. Parallel and sequential design of basic sub-systems in industrial system design.

Sequential design of sub-systems, however, does not imply that sub-systems are designed independently. Consequences of other sub-systems should always be considered. Products should not be designed without consideration of the manufacturing system that is going to manufacture this product. For this, numerous 'design for X'-techniques have been developed. These have been discussed in Chapter 2.

The relations between the basic sub-systems of an industrial system are such that a certain sequence can be prescribed. Since the primary concern of the environment is in the product, product design should be dominant and should precede the design of the production system. A preferred sequence can also be prescribed in the design of the production system. The control system cannot be designed before the design of the manufacturing system, because the system to be controlled needs to be known before the control can be designed. The financial system should be designed serving the manufacturing system. Like the control system, the financial control system cannot be designed before the design of the financial system. Consequently, the preferred design sequence in an industrial system is first the products, second the manufacturing system, third the control system, fourth the financial system and, finally, the financial control system.

Figure 4.5 shows the preferred sequence of sub-systems in an industrial system. It combines knowledge on parallel and sequential design and relations between the sub-systems. This sequence will be used throughout the dissertation, and represented in illustrations from left to right (see for example Figure 4.4).

4.2.7. Conclusion

The division of the industrial system into sub-systems has been discussed in this Section. A division of the industrial system into products and production system has been proposed. The production system, in turn, can be divided into a manufacturing system, a control system and a financial system. Focus in this dissertation is primarily on the design of the manufacturing system and the control system. The design of product and its relations to production system design is also studied.

Advantages as well as disadvantages accompany the division into sub-systems. The parallel design of sub-systems, for instance, may lead to a faster design process. Independent design of sub-systems, on the other hand, may lead to sub-optimal object designs. Advantages and disadvantages have been collated in Section 3.4.
Having dealt with the first axis of the design cube – sub-systems – the second axis will be discussed.

4.3. Design Abstraction in Industrial Systems

After the discussion on sub-systems in industrial systems, the second axis of the design cube will now be treated. The second axis of the design cube is the level of abstraction of the knowledge describing the object design. The division of this axis is called the phasing of the design process. The phasing of the design process has been discussed in Section 3.3.2. In this Section, the phasing of the design processes of the different basic sub-systems will be discussed.

The introduction of phases in the design process requires the determination of the level of abstraction of the structure and certain attributes. The division into sub-systems may be prescribed per phase as well as the level of abstraction of certain attributes. The prescribed aspects of each phasing will be discussed below.

Firstly, the phasing of the product design process will be discussed. Different proposals for the phasing of the product design process have been put forward in the literature. Secondly, the phasing of the manufacturing system design process will be discussed and a proposal will be made. Thirdly, the phasing of the control system design process will be discussed. The literature together with a proposal for phasing will be discussed. The Section will conclude with a review on the division of the design process into different levels of design abstraction.

4.3.1. Design Abstraction in Product Design

Most of the design literature is on the design of products. It is, therefore, hardly surprising that most of the proposals on the phasing of the design process deal with product design. Some of the proposals mentioned in literature will be discussed. It has been shown in Section 3.3.2 that each phasing of the design process is based on subjective reasons. No fundamental reasons can be given to distinguish between two levels of abstraction. The designer is free to choose a phasing that seems most appropriate.

A phasing that is not proposed explicitly, but that reflects the thought that design processes should not be phased, is the use of only one phase. Then, no division is used in the rest of the design process. Simple object designs may not need a division into separate phases. Phasing, however, can help structuring the design process in many cases, even in the case of innovative design. Many different phasings have been proposed. Table 2.1 showed some possible phasings for the product design process, but is far from complete. In information science, for instance, many other divisions of the design abstraction axis have been reported.

All phasings of the product design process are valid. This means that there is no reason to prefer one phasing above another without consideration of the design problem and the designer. If object designs are similar in complexity, the use of a standard phasing is preferable. Project management can be standardised, making communication and evaluation easier.

In this dissertation, a division into three phases will be proposed. This phasing is derived from the Twente school, who distinguish a *function-definition* phase, a *working-principle-definition* phase and a *form-definition* phase. The relation of the phases in product design with the phases in manufacturing system design will be discussed in Section 4.3.2.

In the first phase, the (abstract) functions of which the product consists are determined. Next, working principles to execute the functions designed in the first phase are designed. By doing so, the structure of the product is determined. The eventual form is determined in the third phase. There, details are designed and the object design is concretised. Methods and techniques to support these design phases will be discussed in Section 4.4.2.

The results of the design phases can be visualised in a product diagram. After the first phase, a *function product-diagram* results. A *working principle product-diagram* results after the second phase and after the third phase, a *form product-diagram* results. The structure of the product is illustrated in these design documents. The representation of other attributes may require other design documents. Figure 4.6 shows the three diagrams that are made in the design process of a toy car together with an exploded view of the toy-car. The example of the toy-car will be used throughout this Chapter. A realistic example will be discussed in Chapter 6.

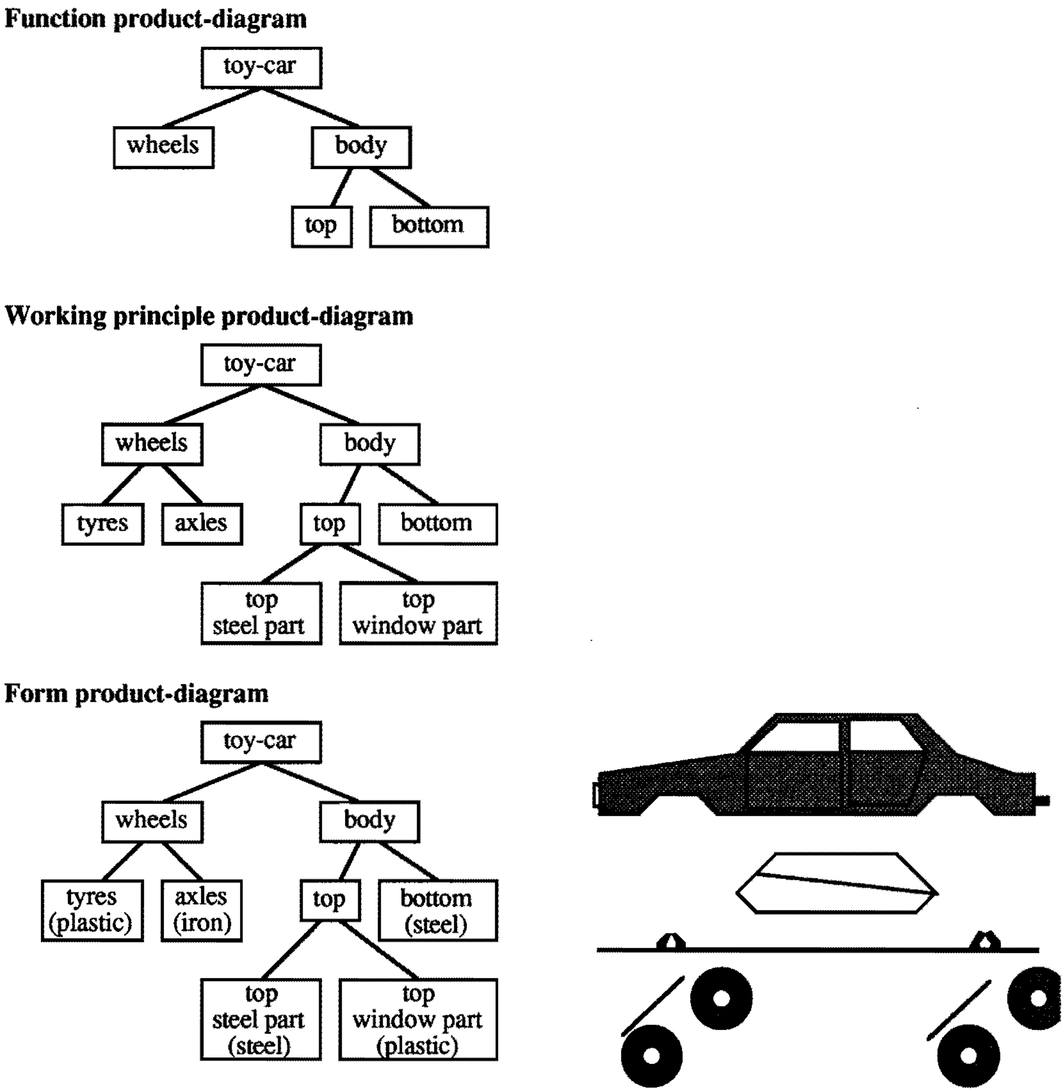


Figure 4.6. Product design documents for the toy-car and an exploded view of the toy-car.

The design of an industrial system most often involves the design of more than one product. The industrial system's sub-system product then consists of a set of products. The design of this sub-system will result in a set of product diagrams, one for each product. These product diagrams are used as a communication means for the manufacturing system design process. This will be discussed in Section 4.3.2 and Section 4.4.2.

Above, design abstraction in product design has been discussed, and different phasings have been presented. A division into three phases is used in this dissertation. Design documents for the three phases have been presented. Next, design abstraction in manufacturing system design will be discussed.

4.3.2. Design Abstraction in Manufacturing System Design

The phasing of the product design process has been discussed in the previous Section. The second axis of the design cube will be treated for manufacturing systems in this Section.

The different phasings proposed for product design, can be used for manufacturing system design too. The domain knowledge incorporated in the phases is, however, based on product design. Names of phases, for example, are based on product design. Besides this, specific manufacturing system aspects are not dealt with.

Another phasing of the manufacturing system design process, therefore, is required. For this, a division into three phases is proposed. The reason for choosing three phases is subjective. Too few phases will not produce a structured design process, whereas too many phases will not produce the overview. The designer can make use of this standard division or he can use the standard division as a starting-point for a dedicated division of the abstraction axis.

The three phases are called processes, processors and means respectively. These names express the level of design abstraction as well as the manufacturing character. In what follows, the three phases will briefly be discussed, and after this, the relations between the phases. The phases will be treated more extensively in the Section on attributes. There, methods and techniques for the solution of the design problems will be treated.

Table 4.5. Phasing of the manufacturing system design process.

<table>
<tr><th>One phase</th><th>Two phases</th><th>Three phases</th><th>Four phases</th><th>Five phases</th><th>Six phases</th></tr>
<tr><td rowspan="6">means</td><td rowspan="2">processes</td><td rowspan="2">processes</td><td>functions</td><td>functions</td><td>functions</td></tr>
<tr><td>processes</td><td>processes</td><td>processes</td></tr>
<tr><td rowspan="4">means</td><td rowspan="2">processors</td><td rowspan="2">processors</td><td rowspan="2">processors</td><td>mechanisms</td></tr>
<tr><td>processors</td></tr>
<tr><td rowspan="2">means</td><td rowspan="2">means</td><td>resources</td><td>resources</td></tr>
<tr><td>means</td><td>means</td></tr>
</table>

Other divisions of the manufacturing system design process consist of more or fewer phases. Table 4.5 shows some possible divisions. In addition to this, the relations between the different phasings can be seen.

Phases in the Manufacturing System Design Process

The first phase of the manufacturing system design process is called *processes*. In this design phase, the processes producing the products are designed. These processes are the most abstract sub-systems in the manufacturing system design process. The design phase will end with a *process-diagram* for each product. Figure 4.8 shows an example of a process-diagram for the toy-car. Figure 4.7 lists the icons that are used for the representation of process-diagrams.

Icons for process-diagrams	Icons for processor-diagrams
manufacturing	manufacturing
assembly	assembly
division	division
transport	transport
storage	storage
inspection	inspection

Figure 4.7. Icons used in process-diagrams and processor-diagrams.

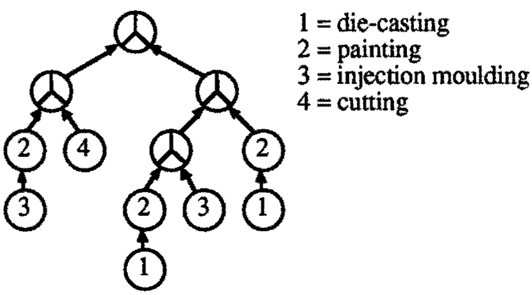


Figure 4.8. Process-diagram of the toy-car.

The process-diagrams are derived from the working principle product-diagram, resulting from the product design process. The basic structure represented in the working principle product-diagram strongly influences the basic structure of the process-diagram. This implies that this structure should be considered carefully. The modular product structure can result in modular manufacturing. The separate modules are assembled after manufacturing. Figure 4.6 and 4.8 illustrate this relationship with the example of the toy-car.

Here, the process-diagrams (and later the processor-diagram) are illustrated such that they should be read from bottom to top. By doing so, the strong relation between the product-diagram and the process-diagram is brought out. The process-diagrams and the processor-diagram can also be drawn in an opposite sense. The sense of the diagrams then better accords with existing diagrams. In any given design process, one single agreed sense is preferred.

The structure represented in the process-diagrams does not necessarily represent the structure of the manufacturing system. The structure of the manufacturing system is determined in the next phase. In this first phase, the structure of the manufacturing of single product types is designed.

Processes are not usually designed from scratch. Rather they are selected from a catalogue of existing processes. Only in rare cases is the development of a new process required. Most often, this will be unnecessary, too expensive or too time-consuming. This design phase will be discussed in more detail in Section 4.4.2.

The second phase of the manufacturing design process is called *processors*. In this design phase, the processors producing the products are designed. These processors are more concrete sub-systems than the processes. The attributes are more precisely known. Attributes like capacity, failure rate, etc. are known only vaguely in the process design phase. Their value is concretised in the processor design phase. The design phase will end with one *processor-diagram* for the entire manufacturing system. Figure 4.9 shows an example of a processor-diagram. The icons that are used in a processors-diagram are listed in Figure 4.7. Again, the toy-car example is used. In this example, the composition of several process-diagrams into one processor-diagram is not incorporated, because there is only one product and, consequently, one process-diagram. This composition problem is treated in Section 4.4.2.

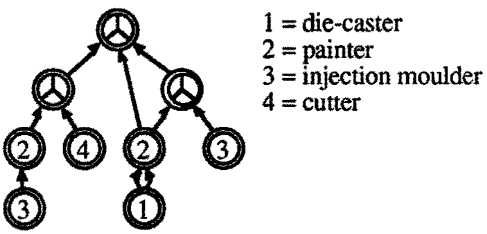


Figure 4.9. Processor-diagram of the toy-car manufacturing system.

The processes are concretised in this design phase. Therefore, the process-diagrams are assembled into one processor-diagram. The processors in the processor-diagram are more concrete versions of the processes. A process X, for instance, may be fast – an abstract value of speed. A processor may take 2 seconds for the manufacturing of a product part – a more concrete description. The second design phase for manufacturing systems will be worked out in Section 4.4.2.

The third phase of the manufacturing system design process is called *means*. In this design phase, the means are designed. Final detailing and concretisation is done in this design phase. The processes that have been concretised in processors are now concretised in means. The machines that will produce the products are concretised or chosen in this design phase. Personnel, manifestations of human processors, is selected.

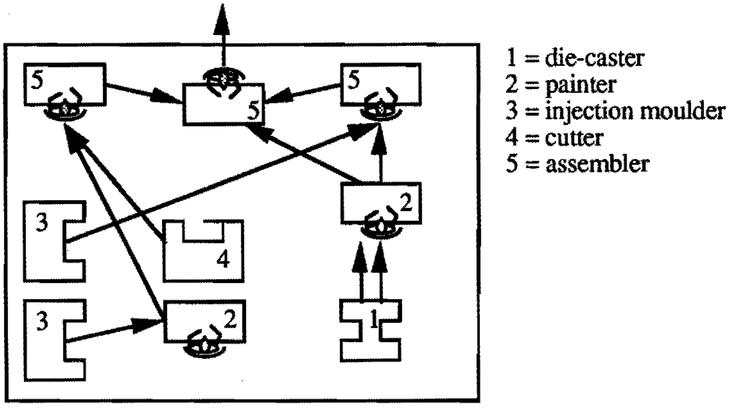


Figure 4.10. Floor-plan of the toy-car manufacturing system.

The physical arrangement is determined. The design phase will end with a *floor-plan* or *lay-out*. Here, floor-plan is preferred above the word lay-out, because of the possible confusion of lay-out and the structure of the manufacturing system, represented in the processor-diagram. Figure 4.10 shows an example of a floor-plan of the toy-car manufacturing system.

Relations between the Phases in the Manufacturing System Design Process

Above, the three phases of the manufacturing system design process have been discussed sequentially. In practice, the design process will not evolve exactly in this way. New insights will force the designers to iterate on earlier decisions. The abstract phase processes, for example, can be reconsidered should the means design reveal high costs. Apart from iteration, another aspect complicates the sequential completion of the phases.

The processes that are selected in the first design phase are derived from the product-diagram. All processes that are essential for the manufacturing of the product are selected in this first phase. Some processes, however, do not follow from the product-diagram and, consequently, are not represented in the process-diagram. Buffer-processes, for example, do not follow from the product-diagram, because they are not essential for the manufacturing of the product.

The eventual manufacturing system contains more processes than incorporated in the process-diagrams. The extra processors, therefore, should be incorporated in the processor design step. This is illustrated in Figure 4.11. From top to bottom, the level of design abstraction decreases. From left to right, the number of processes (and processors) increase. Design, therefore, goes from top-left to bottom-right in Figure 4.11. The processes and processors to be added include buffers and inspectors.

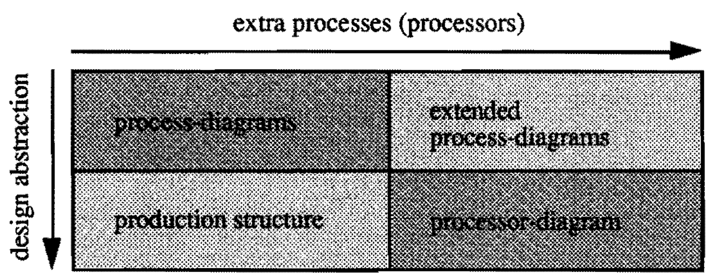


Figure 4.11. The relation between the design of processes and processors.

Figure 4.11 includes the term *production structure*. A production structure is defined as the collection of essential processors (excluding the extra buffers and inspectors) with their material flow relations. The concept of production structure is often used in literature and can be used in the design of a processor-diagram. The paragraphs on the design of the processor-diagram in Section 4.4.2 will also deal with production structures.

A relation can be described between the second and the third design phase, in which the floor-plan is designed, equivalent to that existing between the first and the second design phase. Dimensions are not known in the processors-phase. Transport-processes, therefore, cannot be incorporated, because distances and, consequently, capacities are not known. Dimensions are only determined in the third phase. This is illustrated in Figure 4.12. From top to bottom, the level of design abstraction decreases. From left to right, the number of processors (and means) increases. Design, therefore, goes from top-left to bottom-right. The processors and means to be added include transporters.

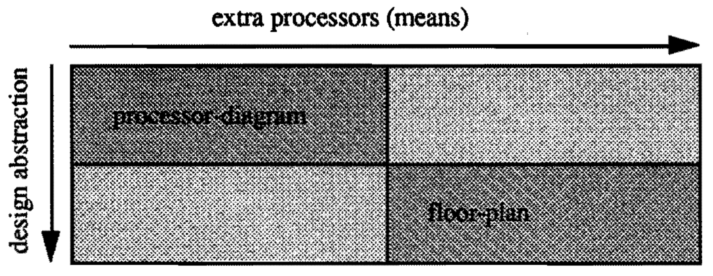


Figure 4.12. The relation between the design of processors and means.

The entire manufacturing system design process is represented in Figure 4.13. From top to bottom, the level of design abstraction decreases. From left to right, the number of processors (and means) increases. The manufacturing system design process, therefore, goes from top-left to bottom-right. The three design phases are shown in Figure 4.13 using a dark shading. It can be seen in Figure 4.13 that the manufacturing system design process is not straightforward. This is illustrated by the shading of the squares.

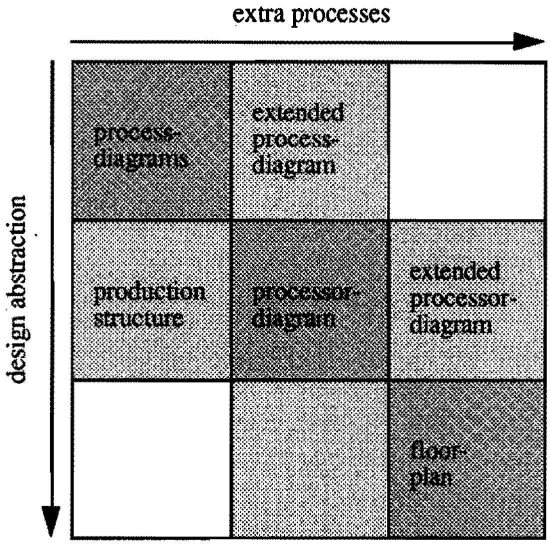


Figure 4.13. The relation between the phases in the manufacturing system design process.

The phases of the manufacturing system design process have been discussed in this Section. Three phases have been proposed and discussed. The relations between the three phases are treated. Paragraph 4.4.2 will deal with the separate design phases individually. There, detailed design methods, developed for the separate design phases, are discussed. Firstly, design abstraction in control system design will be treated.

4.3.3. Design Abstraction in Control System Design

The phasing of the manufacturing system design process is covered in the previous Section. The phasing of the control system design process will be dealt with in this Section. The number of phases that is chosen depends on the complexity of the design problem and on the individual designer. Paragraph 3.3.2 discussed the theory on the phasing of design processes.

Table 4.6 showed some possible phasings of the manufacturing system design process. These proposals can be used for the control system as well. Design documents will differ from the manufacturing system design documents. Here, a division into three phases is proposed for reasons of symmetry with the manufacturing system design process.

Different phasings should be used if necessary. The three phases that can be distinguished are processes, processors and means. The three phases will now be treated consecutively.

The control system design process starts with the design of the *processes*. This design phase can also be divided into two phases [Mulder, 1993]; see Table 4.6. The relations with other design phases and other sub-systems will be treated in Section 4.4.3. Input for this design phase is the manufacturing system processor-diagram. This implies that the structure of the manufacturing system should be designed with great care.
The processor-diagram is decomposed into relatively independent parts, which are controlled by a controller-process. These controller-processes, in turn, are also controlled by a controller-process. This decomposition process is repeated until the control can be carried out satisfactory. By doing so, a system hierarchy or controller hierarchy is formed. The design of system hierarchies is discussed in more detail by Micklei [1993].

The result of the first design phase can be visualised in a process-diagram. To distinguish between the manufacturing system process-diagram and the control system process-diagram, the latter is called a *control process-diagram*. In accordance to this, the former could also be called *matter process-diagram*, since the flow of matter is used in the representation. Figure 4.22 shows the control process-diagram for the toy-car control system. There, the design of the control process-diagram is treated in more detail.

In the second design phase, the processes are concretised into *processors*. Similar processes may be composed into one processor. The result of the second design phase is *control processor-diagram*, in which all processors of the control system are represented. The control processor-diagram of the toy-car example is shown in Figure 4.23. There, the design of the control processor-diagram is treated in more detail.

In the third and final phase of the control system design process, the *means* are designed. The processors, designed in the second phase, are concretised into means. Implementations of the mechanisms, designed in the previous phase, are made. Computer systems are selected and personnel is recruited. The result of the third design phase can be represented using lists of all equipment and personnel and listings of all software. The physical arrangement can be visualised using a *floor-plan*, similar to that discussed in the Section on the manufacturing system design process.

The control system design process has briefly been discussed in this Section. The relations of the phases in the control system design process with other sub-systems will be treated in Section 4.4.3.

4.3.4. Conclusion

The second axis of the design cube, design abstraction, has been discussed in this Section. Different phasings have been proposed for the various basic sub-systems of an industrial system. These standard phasings can be used as a starting-point. The standard phasings may be adapted in actual design processes. More or fewer phases can be used.

The advantages of the use of a division into different levels of abstraction have been discussed in Section 3.3. A clearer overview of over the design process, more control and improved communication possibilities have been mooted as important positive results of phasing the design process.

Besides the advantages, some disadvantages have been mentioned. Since there is no fundamental reason to divide the design process into separate phases, phasing is dependent on the properties of the design problem and the desires and limitations of the designer. Designers' decision making may be hindered by prescribed phases. Designers may not be able to strictly follow the phases. The proposals, mentioned in this Section, therefore, are not prescriptions, but mere guidelines. The financial system and the financial control system can be treated similarly to the manufacturing system and the control system respectively. Figure 4.14 results.

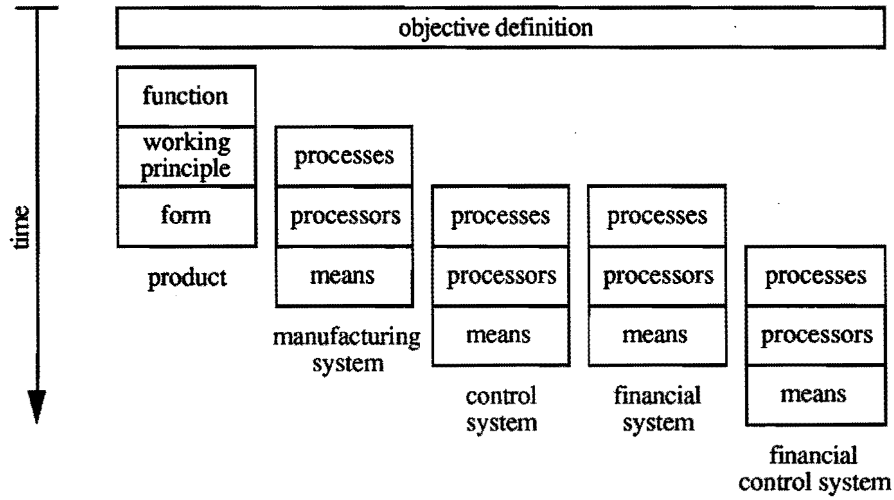


Figure 4.14. The relation between the phases of the different basic sub-systems.

The design processes of the basic sub-systems are related. The discussions above revealed some of these relations. As a result of these relations the entire parallel design of the four-sub-systems is unwise. Sequential design, however, is not necessary. The design processes of the basic sub-systems can be made parallel as presented in Figure 4.5 a and c. Figure 4.14 shows that the design of the manufacturing system processes is done simultaneously with the design of the product structure. The design of the control system processes is done simultaneously with the design of the manufacturing system structure. Paragraph 4.4 will discuss these relations in more detail.

4.4. Attributes in Industrial Systems

Two axes of the design cube have been discussed in the previous Sections. Firstly, the division of the object design into separate sub-systems has been discussed. There, the industrial system has been divided into five basic sub-systems: products, manufacturing system, control system, financial control system and the financial system. Next, the phasing of the basic sub-systems' design processes was been discussed. Phasings for the sub-systems were proposed. The discussion on these two axes of the design cube led to a structure represented in Figure 4.14.

The industrial system design process will go roughly from top to bottom and from left to right in Figure 4.14. The top to bottom direction follows logically from the fact that the design process goes from abstract to concrete. The left to right direction follows from the fact that a sub-system A at the right of a sub-system B cannot be designed without information from B. A manufacturing system, for instance, cannot be designed without knowledge of the products to be produced.

The third axis will be discussed in this Section. The attributes that are relevant for a specific design phase and a specific sub-system will be treated. Other sub-systems will be given attention in the decision-making process. Decision-making is done by the designer, guided by the structured design process in Figure 4.14. This decision-making can be modelled by the general decision cycle, presented in Chapter 2. Attention will be given to methods and techniques that support one or more steps in the decision cycle. In the following sections, the relevant attributes for the decision-making will be treated, as well as the structure of the various design problems. This information can be used by the designer in the decision-making process as well as in the development of supporting methods and techniques.

In other words, the fourth and fifth step in the structuring method will be treated in this Section. This fourth step involves the identification of the relevant attributes in the design problems that resulted after the execution of the first three steps. The fifth step will briefly be addressed in this Section. The fifth step in the structuring of design processes involves the selection and development of supporting methods and techniques for the decision cycle. These methods and techniques can support one or more steps in the decision cycle: (1) analysis, (2) synthesis, (3) evaluation, (4) decision.

The product design process will be discussed first, followed by the manufacturing system design process and the control system design process. Finally, the Section will be concluded with some conclusions concerning the relevant attributes.

4.4.1. Attributes in the Product Design Process

The attributes relevant in the product design process will be discussed in this Section. Since focus in this dissertation is on the production system, only some general remarks will be made. More specific information on this subject can be found for example in the literature on product design mentioned in Chapter 2.

Firstly, attributes in product design will be discussed in general. After this, the three phases that have been proposed in Section 4.3.1 will be treated. Methods and techniques that support the designer in his decision making will briefly be discussed.

The objective attributes are the most relevant attributes. Interested parties outside the system to be designed take interest in that system because of the value of certain attributes. A financier, for instance, will be interested in an industrial system because its return on investment (ROI) is more than 15%. In car design, a customer may take interest in that car because of its acceleration possibilities, its economy or other attributes.

The objective attributes, therefore, should be considered carefully. They cannot always, however, be designed directly. Other attributes, underlying objective attributes, need to be identified. Optimisation towards these attributes, however, should lead to systems that perform optimally with regard to the objective attributes. The Section on objective definition showed some examples of *false* objectives. These *false* objectives are often strongly related to *true* objectives. Consequently, these related attributes should be used with care.

As well as product attributes, attributes of other sub-systems need to be considered. Figure 3.3 showed an example of a network of attributes, describing an object design. In Section 4.2, an industrial system was stated to consist of products and a production system. Figure 4.2 showed part of the two resulting interrelated networks.

Three kinds of relations can be distinguished in Figure 4.2: product-to-product relation, product-to-production system relations and production system-to-production system relations. The latter will be treated in the next Section. Here, the two other kinds of relations will be discussed. The three phases in the product design process will be used to discuss the relevant attributes and the relations with other sub-systems. The methods and techniques discussed below deal with many different attributes.

Function Design in Product Design

The first phase in the product design process also is the first phase in the industrial system process. Decisions, therefore, in this design phase are instrumental in determining the eventual quality of the industrial system. Numerous methods and techniques have been developed to support decision making in this design phase.

The techniques that can be used for the generation of concept solutions are the general design methods that have been mentioned in Chapter 2. Brainstorming, Delphi method, Method 635 and Synectics are some examples. These techniques can be used in other phases too. These techniques all support the synthesis step in the decision cycle. The methods Objectives Tree, Functional Analysis and Performance Specification are especially suited for the support of decision making in this design phase [Cross, 1991]. The latter techniques support the analysis and evaluation steps of the decision cycle.

Recently, researchers spend more effort in the formalisation of the abstract design phases in product design. This increase in effort is dictated by the relevancy of this design phase Examples have been discussed in Section 2.3.2. No techniques are known to study the relation of the object design in this design phase and other sub-systems. Although relations must exist, relations are still too weak to formalise.

Working Principle Design in Product Design

The previous design phase ends with a function product-diagram. All functions comprising the product are incorporated in this diagram. The functions are worked out in the second design phase. Working principles are chosen for each function. One working principle may perform one or more functions and a function may be performed by one or more working principles. The concepts of composition and decomposition have been discussed in Section 3.4.1. A method that is applicable in this design phase is Morphological Analysis [Zwicky, 1969], in which the designer is pointed to other possible principal solutions. Morphological Analysis can also be used in other design phases.

The product structure is determined in the second design phase. It was shown in Section 4.3.2 that product structure and manufacturing system processes are strongly related. This relation, therefore, must be studied in this design phase. This implies that process selection, discussed in Section 4.4.2, should be carried out simultaneously with the determination of the product structure.

Most of the methods and techniques that have been developed to study the relation between product and manufacturing system design can only be used in the most concrete design phase. The ideas behind the techniques, however, can also be used in this design phase. One example is offered: Design for Assembly [Boothroyd, Dewhurst, 1983] , which aims at the optimisation of product design concerning assembly. The detailed design method can only be used in the form phase, because every attribute of the product design needs to be known. The ideas behind DfA, however, can also be used in the working principle phase. DfA is based on the conviction that fewer components result in cheaper assembly. Since the product structure is determined in this phase, the three basic question of DfA can be used. If one of the answers to these questions is *yes*, integration or elimination of the component is impossible. Figure 4.15 shows the three basic questions of DfA. DfA supports both the analysis step and the synthesis step in the decision cycle.

1. Should the part be able to move relative to other parts ?
2. Should the part be of a different material than other parts ?
3. Should the part be removable (for maintenance, etc.) ?

Figure 4.15. The three basic questions of Design for Assembly [Boothroyd, Dewhurst, 1983].

Numerous techniques have been developed to support decision-making in the product design process. Most of these techniques have been developed for the most concrete design phase. The ideas behind these techniques, however, can sometimes be used in other design phases too. Examples are, besides DfA that studies product-to-manufacturing system relations, CAE-techniques that study product-to-product relations. Basic Mechanical Engineering formulas can be used to evaluate the performance of mechanical structures .

Another approach for the solution of design problems in more abstract phases of the design process is the use of general design methods. These methods have been discussed in Section 2.3.3. Examples are Axiomatic Design, the Algorithm for the Solution of Inventive Problems (ASIP) and general techniques like Brainstorming and Synectics. These techniques support the synthesis step in the decision cycle.

Form Design in Product Design

Most techniques developed for product design have been developed for the most concrete design phase. Historically, the product-to-product relations have received most attention. Methods and techniques have successfully been developed. The Finite Element Method, for instance, can be used to evaluate the product performance concerning kinematic and dynamic behaviour [Zienkiewicz, Taylor, 1989]. It supports the evaluation step of the decision cycle.

The product-to-production system relations, have attracted interest in recent years. A growing understanding that products should be designed with consideration of the production system, has led to a growth of scientific research and practical attention. Since relations between product and manufacturing system are most apparent, these relations are the most studied.

Many 'Design for X'-methods (DfX-methods) have been developed. Design for Assembly (DfA) was one of the first methods to investigate the relation between product and manufacturing system. DfA optimises the product design concerning the assembly of the product. In DfA, assembly is claimed to be an important and costly operation in the manufacturing. Optimisation, therefore, will lead to cheaper and better manufacturing systems. Other DfX-methods have been reported. Some examples have been mentioned in Section 2.3.2.

The DfX-methods all optimise a particular set of attributes. The global optimum, therefore, is not attained. The result of a DfA procedure, for instance, may be a product that is cheaper to assemble, but more expensive to produce. DfA strives for a minimum number of parts, but those parts can be more complex and, therefore, more expensive to produce. The designer is expected to watch the values of other attributes while applying a DfX-method.

Conclusion

Many methods and techniques have been developed to support the product design process. Most techniques are applicable in the concrete phases of the design process. Ideas behind the techniques, however, can sometimes be used in more abstract phases. Examples of detailed design methods have been given. Most of current design research is done in product design. The formalisation of product design, however, requires more research, especially on the more abstract phases.

The product design process has been discussed in this Section. More information and more methods and techniques are treated in the numerous handbooks on product design, mentioned in Chapter 2. In the industrial system design process, product design is followed by manufacturing system design. The next Section will deal with the manufacturing system design process.

4.4.2. Attributes in the Manufacturing System Design Process

After the design of the products, the manufacturing system is designed. Design of the manufacturing system can in part be executed in parallel with the design of products. This has been discussed in the previous sections. The relations between product design and manufacturing system design will be discussed in more detail in this Section.

Manufacturing system design has already been treated twice in Section 4.3.2. Firstly, the three phases in the manufacturing system design process were discussed individually. Secondly, the relations between the three phases were dealt with. Now, the three phases will be treated individually. Relations with other sub-systems and other phases will be dealt with. Methods and techniques that support decision making will be discussed in this Section.

Firstly, the most abstract design phase in which the processes are designed will be treated. Secondly, the design phase processors will be treated. Thirdly, the most concrete design phase in which the means are designed will be treated. Finally, the manufacturing system design process will be reviewed. Each discussion on the design phases is structured identically. The input to the design phase will be discussed first. Following this, attention will be paid to the relation with other sub-systems. This information is used in the analysis step of the decision cycle. After this, the decision-making process will be discussed.

Methods and techniques will be presented, starting with, the design of the structure of the elements will be treated, and then the design of the elements themselves.

Processes

The first phase in the manufacturing system design process is called *process design*. The phasing is the result of a division into three levels of abstraction, discussed in Section 4.3.2. Figure 4.16 shows process design in relation to other design phases and other sub-systems. In Figure 4.16, the attributes axis is added. Firstly, the input to this design phase will be discussed. Secondly, attention will be paid to other sub-systems. Thirdly, the design of the structure will be treated. Finally, the design of the elements designed in this phase will be treated.

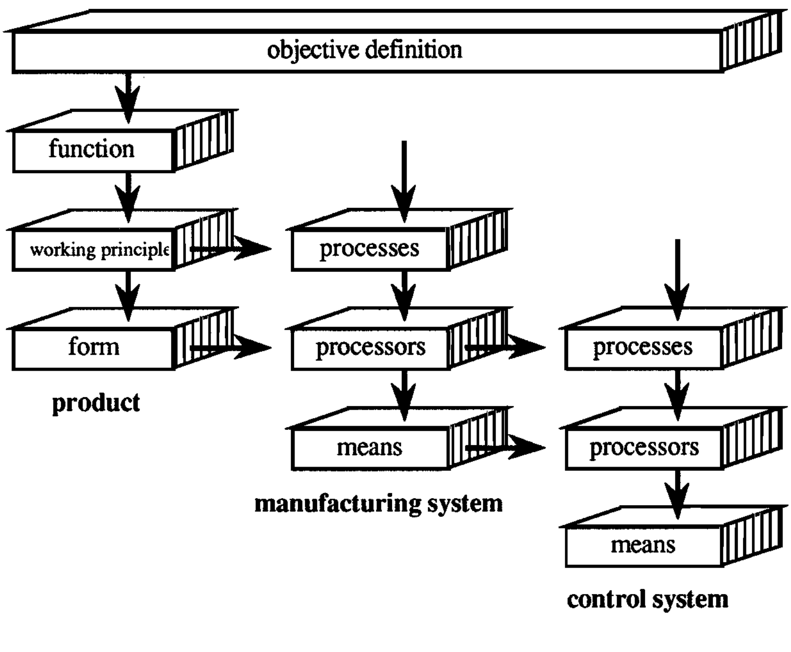


Figure 4.16. Design phases in industrial system design in relation to other phases and basic sub-systems.

The attributes relevant to the design phase are represented by the vertical hatching in Figure 4.16. In doing so, the third axis of the design cube is added to the structured design process illustrated in Figure 4.14. Figure 4.16 shows that the industrial system's objective and the product design phases function and working principle are all inputs for the process design phase. In a sequential design process, knowledge on the concrete form can also be taken into account. Paragraph 4.3.2 discussed the relation between product design and manufacturing system process design.

Attention should be paid to the design of the control system. Although the design of the control system can only be started in parallel with the processor design phase, consideration of the control system is relevant. One process may be easier to control than another. The selection, therefore, of a process should take its controllability into account. Not considering the control system in the process design phase may lead to expensive iteration.

After the input to the design phase and other sub-systems have been discussed, the decision making process will be treated. Firstly, the design of the structure will be treated. The structure consists of the elements to be designed in this design phase. These are the processes, the most abstract elements in the manufacturing system design process.

The structure of the process is represented by a process-diagram. It has been shown that the structure of the process-diagram is similar to the structure of the product-diagram. This product structure is determined in the working principle design phase. Therefore, the process design can be carried out in parallel to the product working principle design. Below, the relation between process design and product design is discussed in more detail.

The structure of the process-diagram can deviate from the product structure, because more than one process is required to manufacture a single element. A process to be selected for a single element can consist of sequence of processes. This can be illustrated with the toy-car example. The manufacturing of the iron top of the toy-car consists of two steps. Firstly, the iron is die-casted and secondly, it is painted. This is illustrated in the process-diagram of the toy-car; see Figure 4.8. Another example of multiple processes for one product element, is the application of a pre-treatment or a finishing process.

Next, the design of the elements will be treated. The purpose of the process design phase is a collection of process-diagrams. One process-diagram is constructed for every product (or product-type). Processes need to be designed for every element in the product structure, and attributes that are relevant for this design phase need to be identified. Geometric attributes such as dimensions and tolerances should be taken into account. Different processes have different geometric capacities. One process, for instance, may deal with large products and low tolerances, whereas another process may be suitable for small products with high tolerances. Differences in geometric capacities are discussed in many handbooks (for example [Kalpakijan, 1991]).

Material attributes such as brittleness, strength and thermal conductivity should also be considered. Different processes are suitable for different sets of materials. One process, for example, may cope with very brittle material, whereas another process may be suitable for very tough materials. Injection moulding is suitable for polymers and not for metals. Casting can be applied for metals, but not for wood. Differences in material capacities are also discussed in many handbooks.

This implies that process design cannot be done before the determination of these attributes in product design. The function design phase determines the functional elements of the product. Attributes like those mentioned above are only roughly known. The function power supply in car design, for instance, can lead to the application of a limited set of working principles. Materials suitable for this task are many, but nevertheless the application of for example wood has become unlikely. Product attributes, however, are too inexact to be able to make definite decisions on process design.

Product attributes become more precisely known in the second design phase: the working principle definition phase. If, for instance, the Otto-engine has been chosen as a working principle for the function power supply, geometrical and material attributes are further constrained. The application of certain metals or ceramics is likely. Process design, therefore, can in part be carried out concurrently with the product working principle design.

The product attributes, however, are only determined in the most concrete phase. Geometric and material attributes also are determined in the form design phase. Process design, therefore, cannot be completed before the completion of product design. Nevertheless, important structural choices are made in the working principle phase. Therefore, in Figures 4.14 and 4.16, the process design phase is drawn alongside the working principle phase. After the relation of process design with product design has been discussed, the design of processes will be discussed in more detail.

Processes are often not newly designed. Selection of already existing processes is faster, safer and requires less expertise. Consequently, most of the methods and techniques developed for this design phase focus on process selection. The design of new processes is applied if, for instance, new materials are to be used, higher tolerances are required or larger production series are demanded.

Before considering detailed design methods for process selection, the structure of the problem will be studied. This discussion will reveal that most detailed design methods deal with only a small part of the actual process design phase.

The purpose of the process design phase is a collection of process-diagrams. Process design, therefore, should not focus on the design of a single process, but on the design of the entire set of processes. Processes need to be selected for every element of every product. These processes should be evaluated using appropriate attributes. Manufacturing system attributes as well product and control system attributes should be considered. Process selection, therefore, is a function of all elements of all products, all possible processes and all relevant attributes.

This model of process selection states that all elements of all products should be considered simultaneously. By doing so, sub-optimisation is prevented. The optimal process for one element may be sub-optimal for the entire manufacturing system. An example will demonstrate this. The optimal process for a particular element may be a process A. The optimal process for another element may be a process B. An integrated approach, however, may reveal that the selection of process A for both elements is preferable. Processor design may combine both processes A into one processor, resulting in a cheaper manufacturing system. This would be impossible if two different processes were applied.

Variants on the process selection model can be given. These variants are simplifications of the initial model. The first variant considers all elements within one product, whereas the second variant considers a single element. Most process selection models presented in the literature are variants of the latter model. The optimal process is selected for the manufacturing of one component. Using these variants, the designer should prevent sub-optimisation by considering other elements and other products.

Themes on the second variant of the ideal model for process selection differ regarding the attributes they consider. Most of the models presented in literature consist of two steps. The first step is a pre-selection of processes that are able to manufacture the elements. All processes that are technically unsuitable are eliminated in this first step. Product attributes are used for this pre-selection. Next, the remaining processes are compared using some (set of) attributes(s). The predominant attribute is cost. The cheapest process that is able to manufacture the product is selected in this second step.

A summary of process selection models is given in Smeets [1993]. Most models for process selection presented in literature are instances of the second variant of the ideal model. Only one element of only one product is considered simultaneously, only few processes are taken into account, and few attributes are weighed. Process selection models as presented in literature, therefore, are inherently sub-optimal.

Figure 4.16 showed the relation of process selection with other sub-systems and other phases in the manufacturing system design process. None of the models found in literature consider other phases. The only other sub-system is the product, whose attributes are used in the (pre-) selection of processes.

Consideration of the control system may be included in the process selection models by including ratings of controllability. One process may be easy to control, whereas another product may require difficult and expensive control. A process may be capable of producing a particular product with particular dimensional attributes. The control, however, may be so complex that, for example, rejection rates are high.

The consideration of other phases may also be included in the process selection models. The application of processes that result in the use of an expensive processor will cause problems in the structure design. Multiplication of these processors, however logistically interesting, is then rejected for financial reasons. The relation with the design of means should also be considered. The application of processes that result in large means will cause problems in the floor-plan design. Consideration of these effects in the process selection will avoid these problems. The impact of the means design will be relatively small, however.

The design of processes has been discussed in this Section. Most often, processes are not newly designed but selected from a set of already existing processes. Many process selection models have been presented in the literature. These models support all four steps in the decision cycle. It has been shown that they are inherently sub-optimal. Most models focus on cost by selecting the cheapest process capable of manufacturing the product.

Other sub-systems and more concrete phases of manufacturing system are not taken into account. Only a small set of attributes is used for the selection of the best process. The designer, therefore, should consider other attributes, sub-systems and phases to avoid sub-optimisation. The support given by the methods to the four steps in the decision cycle, therefore, is only limited.

After the design of processes, the manufacturing system design process proceeds with the design of processors. These processors are concretisations of the processes. The design of processors will be discussed in the next Section.

Processors

The second phase in the manufacturing system design process is called processor design. The processes designed in the first design phase are concretised in this phase. Figure 4.16 also shows the processor design in relation to other design phases and other sub-systems. Firstly, the input to this design phase will be discussed. Secondly, attention will be paid to other sub-systems. Thirdly, the design of the structure will be treated. Finally, the design of the elements designed in this design phase will be treated.

Figure 4.16 shows the relation of the processor design phase with other phases and other sub-systems. Input for the processor design phase is the collection of process-diagrams, as well as the objective of the industrial system and the result of the product design process.

Figure 4.16 also shows the relation of processor design with other sub-systems. The process design phase of the control system can be executed in parallel to the design of the processors in the manufacturing system. Consequently, attention should be paid to the control system. The control system should also be studied in a sequential design process. There is strong relationship between the structure of the manufacturing system, that is determined in this phase, and the control system. Later in this Section, this relationship will be discussed in more detail.

After discussing the input to the design phase and other sub-systems, the decision-making process will be treated, starting with the design of the structure. The structure consists of the elements to be designed in this design phase, namely the processors. Processors are concretisations of the processes, designed in the previous design phase.

The previous design phase ends with a collection of process-diagrams. The purpose of the processor design phase is to produce one processor-diagram for the entire manufacturing system. The process-diagrams, therefore, need to be composed into one processor-diagram. This composition process will be discussed in this Section. Firstly, however, the attributes and sub-systems relevant in processor design will be discussed.

Since the structure of the manufacturing system is designed in this phase, evaluation should take place using attributes referring to this structure. The structure should be evaluated using objective attributes. The objective attributes in Table 4.1 that are most closely related to structure are the cost and time-related attributes. Other attributes, however, can indeed be effected by structure. Quality, for instance, may be higher in a line structure where fast feedback is possible on errors made, than in a more complex functional structure, where feedback is much slower.

After the synthesis of the structure, the design decision needs to be evaluated. Evaluation can be done using appropriate evaluation techniques. Simulation techniques can be used to evaluate the behaviour of the object design concerning time-related attributes. Many simulation techniques have been reported. Chapter 2 gave some examples. Cost evaluation techniques have been documented in standard economic literature (for example [Aragon, 1989]). The evaluation of other attributes is still only barely formalised. The relation of structural attributes with quality, for example, is not formalised at all. Evaluation, therefore, should be done using expert knowledge. Summarising, it can be stated that the third step in the decision cycle, evaluation, is only supported concerning time- and cost-related attributes.

After the attributes relevant to processor design have been discussed, the design of the processors will be treated. Firstly, the design of the structure will be addressed. Secondly, the concretisation of processes into processors is discussed. Design and selection of working principles in manufacturing system design will be treated.

The design of the structure of a manufacturing system can be done using production structure typologies. Paragraph 4.3.2 has given the definition of production structure. Extra processors need to be added to the production structure to get a processor-diagram. The production structure typologies present a classification of all possible structures. Many typologies have been reported in the literature. Together with a basic structure, some attributes of that structure are described. A flow-shop, for instance, has high productivity, but low flexibility. A job-shop, on the other hand, has low productivity, but high flexibility.

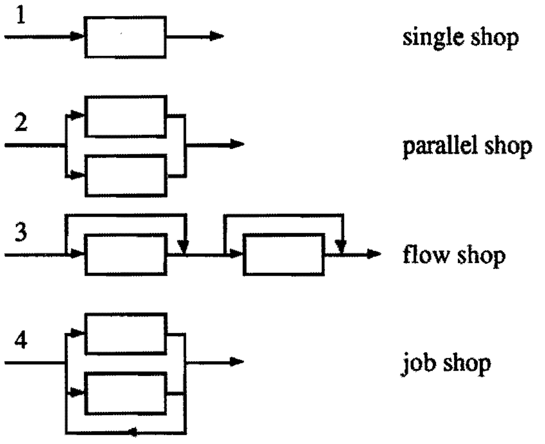


Figure 4.17. Four basic structures [Smit, 1992].

Figure 4.17 shows four basic structures that can be used to compose production structures [Smit, 1992]. Smit distinguishes the single shop, the parallel shop, the flow shop and the job shop. All production structures can be assembled using these building blocks, and then classified. These production structures can be represented using an incidence-matrix or cross-matrix [Mulder, 1992]. Figure 4.18 presents an example of production structures. Production structures and processor-diagrams can be classified using this matrix. Appendix A illustrates the possibilities of the incidence-matrix representation and shows some typical examples of production structures. The analysis step in the decision cycle is supported with this representation technique.

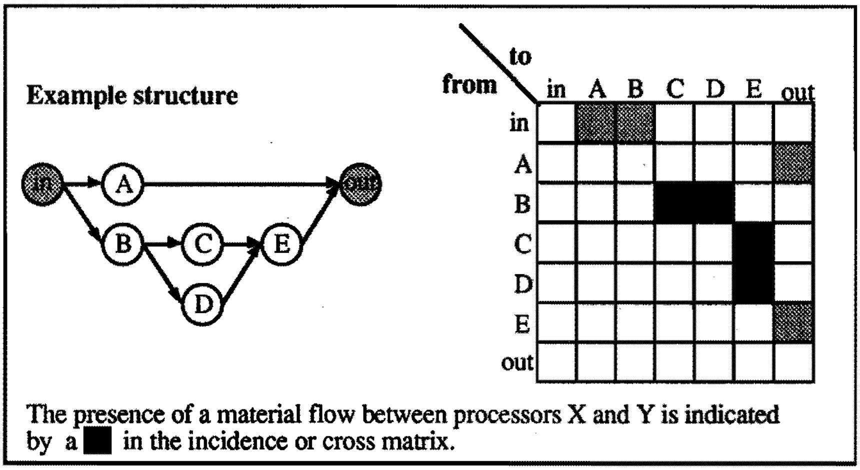


Figure 4.18. Representation of a production structure using the incidence matrix.

The design of the structure of a manufacturing system can be done using production structure typologies. Typologies, however, can only be used to give direction to the design process. No detailed solutions are presented. The designer needs to detail the solution presented. Formal methods to detail solutions exist only for a small subset of possible structures. If knowledge in typologies directs towards the use of groups, formal methods to create groups can be used. These methods are part of Group Technology [Burbidge, 1971, 1989]. Methods to form groups are discussed by Hyer and Wemmerlöv [1986] and Ruffini [1994].

Currently, no formal methods exist to design processor-diagrams in one step. The structure of such a one-step method follows from the structured manufacturing system design process. Figure 4.19 shows an example. The design starts with the collection of all process-diagrams. These are connected such that the manufacturing system consists of lines, all producing one product-type. All processes are concretised to processors. A number of composition actions will eventually lead to an optimal production structure. Addition of extra buffer- and test-processors will yield the processor-diagram. The design of production structures and processor-diagrams has been discussed in more detail by Mulder [1992] and Van Bree [1993].

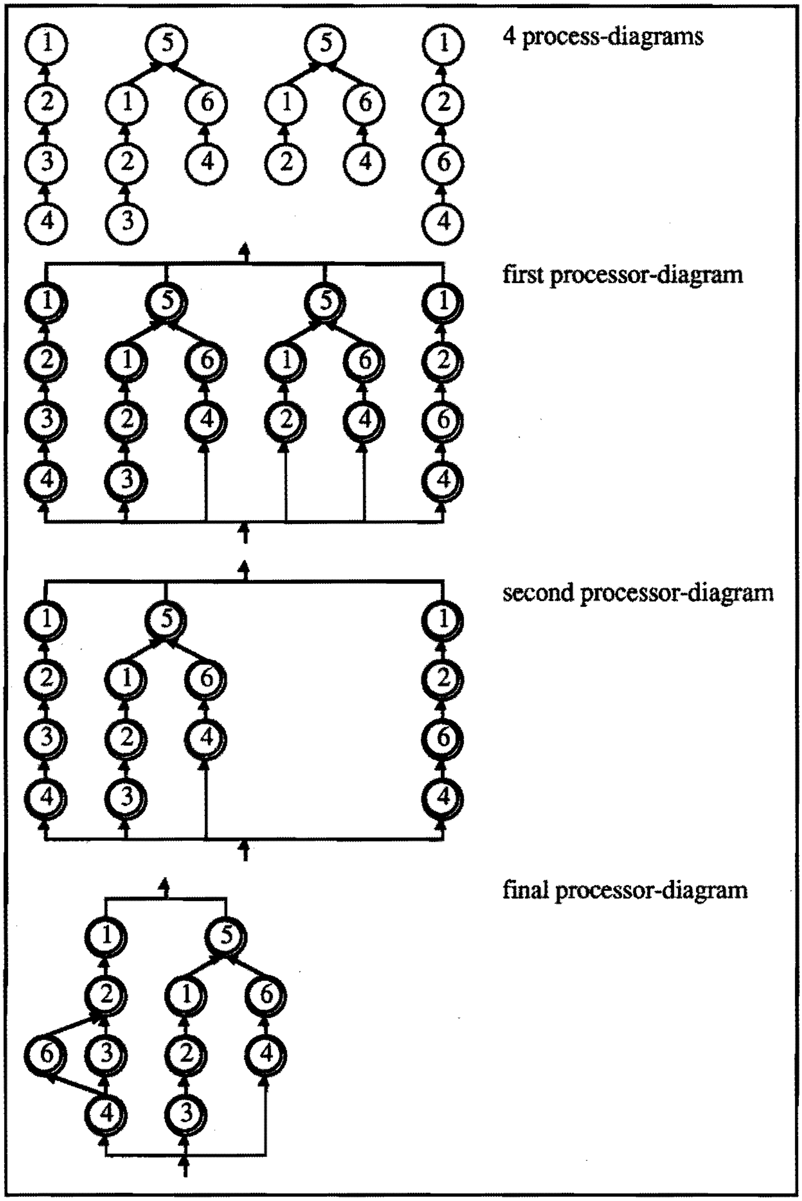


Figure 4.19. Example of a production structure design.

The four steps in the decision cycle concerning the design of the structure of the manufacturing system are partially supported. Instruments for the analysis of existing processor-diagrams have been presented. A structure that can be used to develop a method for the synthesis of processor-diagrams has been presented. Currently, production structure typologies and group-forming methods can be used in the synthesis step. The evaluation of the processor-diagram is supported by simulation techniques supporting the modelling of time- and cost-related attributes. Final decision making is supported by conventional techniques in Wertanalyse and Value Engineering.

The design of the structure of the manufacturing system has been discussed above. Next, the design of the elements in the structure will be treated. The elements discussed here are the processors. Processes are concretised in the design of a processor-diagram. Comparing the manufacturing system design process with the product design process reveals that the processor design phase is equivalent to the working principle design phase. This implies that working principle for the processes are designed in the design of the processor.

Mechanism and *algorithm* are synonyms for *working principle*. The design of the processors, therefore, requires the design of mechanism or algorithms that will perform the processes. The design of working principles is supported by the use of known working principles. Standard modular and parametrised computer programs, for instance, can be used to model processors.

Many modelling techniques have been described to model working principles. Flow-charts, computer languages, and so on can be used. The available modelling techniques for machine design originate in product design. CAD-techniques are used to model geometrical attributes of processors. CAE-techniques are used to evaluate the kinematic and dynamic behaviour of processor constructions. These constructions are concretised in the means design. There, for instance, material selection will take place.

The modelling of the processors requires the description of these working principles (mechanisms or algorithms). For some human tasks, however, formal modelling of the working principle is not possible. Then, an abstract description is used. In this way, human tasks can also be evaluated. In the design of the means, the working principles are concretised. This implies that personnel is selected and physical means are designed or selected.

Means

The third phase in the manufacturing system design process consists of the means design. The final concretisation is done in this design phase. Processors designed in the previous phase are concretised. Figure 4.16 shows the design of means in relation to other design phases and other sub-systems. Firstly, the input to this design phase will be discussed. Secondly, attention will be paid to other sub-systems. Thirdly, the design of the structure will be treated. Finally, the design of the elements designed in this design phase will be treated.

Figure 4.16 shows the relation of means design with other design phases and other sub-systems. The design of means uses information on the objective of the industrial system, the concrete product and the manufacturing system design phases processes and processors. Direct input to this design phase is the processor-diagram. The result of the means design is a collection of means that is able to produce the products.

The design of the means will influence the design of the control system. Attention, therefore, should be given to control system design. The design of manufacturing system means is carried out in parallel to the design of control system processors. The working principles (algorithms) are determined in this phase. Concrete attributes of the means can have strong influence on the working principle selection. The processors in the control system are constrained by the attributes of the manufacturing system. Means that are highly unstable demand different control algorithms than stable means. The selection or design of means should, therefore, consider the consequences for the control system. A machine that is more expensive but easier to control may be a better choice than a cheap machine.

After the input to the design phase and other sub-systems have been discussed, the decision-making process will be treated. Firstly, the design of the structure will be treated. The structure consists of the elements to be designed in this design phase. The elements to be designed are the means. Means are concretisations of the processors, designed in the previous design phase.

The equivalent of the means design in product design is the design of form. After the working principle has been designed in the second design phase, the product design process is completed in the form design. The physical form of the product is determined. Similar in manufacturing system design, the physical form of the processors is determined.

The attributes, therefore, that are relevant to means design have strong relationships with form. Evaluation of the means is equivalent to the evaluation of the concrete manufacturing system. Evaluation, therefore, should take place using all objective attributes. Cost as well as time-related attributes and quality should be taken into account.

The structure of the manufacturing system is determined in the processor phase. In this phase, the structure is concretised in a physical arrangement of the means. The arrangement of the means is represented in a floor-plan. Many formal techniques exist that support the design of floor-plans. Muther has described a method for the design of floor-plans [1963]. More recently, similar methods have been described [Roushop, 1991; Van Neer, 1992]. These methods support all four steps of the decision cycle.

Currently, computerised methods are available. Examples are CORELAP [Lee, Moore, 1967], MODULAP [Minten, 1975] and SCALP [Lintermans, Renders, 1989]. A computerised method that makes use of Genetic Algorithms [Goldberg, 1989] has also been implemented [Van Dijk, 1993]. These techniques support the synthesis and evaluation of floor-plans.

The attributes that the various methods use for optimisation differ. Most of the methods use the minimisation of transport distances as an objective. By doing so, the objective attribute cost is minimised, because transport distance is related to transport capacity. Some methods include the optimisation of other relations between means in their optimisation. A machine that strongly vibrates should not be placed near a highly sensitive machine. The objective attribute quality can thus be optimised.

Often, the design methods for floor-plan generation are used in a redesign situation. The only difference between design and redesign is the knowledge of means that are already available. The applicability of these methods for redesign, therefore, requires the use of information on these means. Constraints that exist, for example, because of the existence of special foundations should be taken into account. In a new design, special foundations will be laid down where necessary, whereas in redesign means sometimes need to be placed on apparently sub-optimal places. Currently, no method is capable of optimising the floor-plan while taking these constraints into account. Ideally, cost optimisation should also consider the cost of eliminating or changing existing constraints. In addition to this, all objective attributes should be used for the evaluation of floor-plans.

Having discussed the design of the means' structure, the design of means will now be addressed. The equivalent of means design in product design is the design of form. Consequently, the processors are concretised into form in this design phase. The physical form is determined in this design phase. Means can be designed or can be selected from a catalogue.

Most means in a manufacturing system are selected from a catalogue. Individual adaptations will be made such that the desired working principle (processor) is attained. In special cases, however, means do not exist commercially. This implies that the means have to be designed. Techniques are available to support this design step. CAD-techniques, originating in product design are used for the design and modelling of the means. CAE-techniques are used for evaluation. Mathematical expressions are used to calculate and evaluate construction of means.
The selection of personnel is a speciality in itself.

Review of the Manufacturing System Process

The manufacturing system design process has been discussed three times. Firstly, the three phases have been discussed sequentially in Section 4.3.2. Secondly, the relation between the three phases has been discussed in Section 4.3.2. Finally, the three phases have been discussed in more detail in Section 4.4.2.

The discussion revealed that the manufacturing system design process can be divided into three phases. The relations between the phases are strong, however. The design documents that result from the three phases can be seen as interim design results. The design process is not a linear process that consists of a number of consecutive steps. The introduction of the design documents, however, points the designer to essential decisions in the manufacturing system design process.

Techniques that support decision-making in the three phases have been discussed. It showed that many techniques only take few attributes into account. Cost minimisation is predominant. Besides this, most optimisation techniques are *single-objective*. This means that only one objective attribute is used in optimisation. It has been shown that industrial system design is inherently *multi-objective*. Optimisation of object designs, therefore, is only applicable for some small well-defined design problems.

Therefore, modelling techniques have been developed that can be used for the evaluation of other attributes. An example is the use of simulation for the evaluation of time-related attributes. Optimisation of the object designs is done by iteration. The object design is modelled and evaluated. If evaluation fails, changes are made and, again, evaluation takes place. By doing so, the design process is supported regarding evaluation. The designer is still responsible for the other steps of the decision cycle and, consequently, for the quality of the object design.

Above, the manufacturing system design process has been treated. Following, the attributes in the control system design process will be discussed.

4.4.3. Attributes in the Control System Design Process

The manufacturing system design process has been discussed in the previous Section. The next basic sub-system that will be designed in the control system. Figure 4.16 shows the relation of the control system design process with other design processes. The three phases that have been introduced for the control system design process in Section 4.3.3 will be treated consecutively. The discussion on the control system design phases will be structured similarly to discussion on the phases in the manufacturing system design process.

The design of the control system can be seen as the parallel design of hardware and software. Many software design methods have been reported in the literature. Software development methods are discussed in numerous books (e.g. [Van Vliet, 1984; Rumblaugh et al., 1991; Stevens, 1991]. The methods discussed in these books can be used to support software development. Here, both software and hardware design will be discussed.

Processes

The first phase in the design of the control system involves the design of the processes. Firstly, the input to this design phase will be discussed. Secondly, the design of the structure will be treated. Finally, the design of the elements designed in this design phase will be treated. It can be seen in Figure 4.16 that the input for this design phase comes from the manufacturing system processors design and the definition of the objective. Input for this design phase, therefore, is the processor-diagram. The relation of the manufacturing system's structure to the control system is, therefore, strong.

Secondly, the design of the structure of processes in the control system will be treated. In this first phase, the basic system hierarchical structure of the control system is designed. The design of the system hierarchy can be done in two steps [Micklei, 1993]. The first step involves the stepwise decomposition of the manufacturing system into parts logically belonging together. Each of these parts is controlled by a controller. Each of the controllers formed in this way is co-ordinated by an extra controller. Figure 4.20 illustrates this design step. The reason for the decomposition is that one controller would be too complex for the entire underlying system. The decomposition process ends if all resulting controllers have satisfactory complexity.

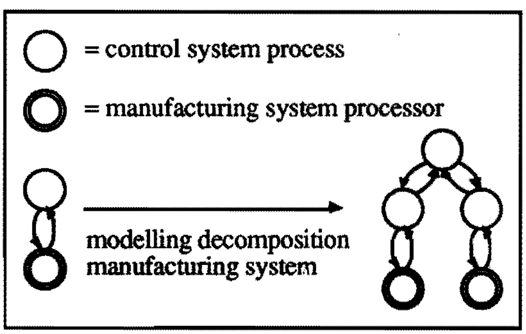


Figure 4.20. The design of control structure based on the manufacturing system structure.

Numerous reasons exist for the decomposition of the manufacturing system. Similar machines (processors) may be grouped together in a job-shop situation. Production lines may be grouped together in a group technology situation. The Customer Order Decoupling Point (CODP) can be used in the decomposition. After the decomposition, the part before

Secondly, the design of the processor structure will be discussed. The basic system hierarchical structure has been designed in the previous design phase. As a consequence, the structure will be only slightly altered in this design phase. If two or more processes perform similar tasks, a designer may decide to compose these processes into one processor. Reasons for this may include lower cost, ease of data access or data consistency.

Thirdly, the design of the elements will be treated. The elements in this design phase are the processors in the control system. The mechanisms, still abstract in the previous phase, become more concrete in this phase. Here, the algorithms are selected or developed. The evaluation of the processors of a control system with respect to their behaviour in time can be carried out using modelling and simulation techniques, examples which have been mentioned in the Section on the design of processors in the manufacturing system.

The selection or development of the algorithms is dependent on the attributes of the manufacturing system. An accurate manufacturing system requires different control than a manufacturing system with high rejection rates. A manufacturing system where control response times are measured in seconds or even shorter, requires different control than a manufacturing system where control response times can be hours or even days. Relevant attributes in the control system design are the objective attributes, since the control system is intended to control the manufacturing in such a way that the objective attributes are maintained or achieved.

The result of this design phase is shown in a control processor-diagram. The processors are represented by a double circle. Figure 4.23 shows the control processor-diagram of the toy-car control system. The assembly control processes have been integrated into the assembler's tasks. Therefore, the control processor-diagram has less system hierarchical levels in the assembly part.
This is an example of a composition action of processors belonging to two different basic sub-systems. It illustrates the importance of continuously considering the relation between the basic sub-systems.

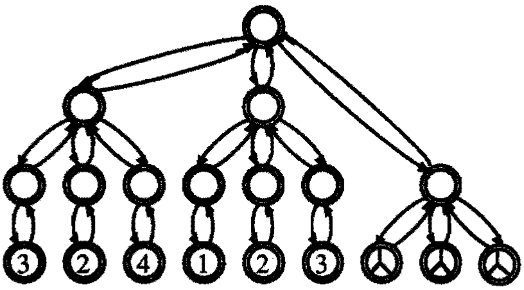


Figure 4.23. The control processor-diagram of the toy-car control system.

In this Section, the design of the processors in the control system has been treated. Methods and techniques to support the four steps in the decision cycle can be developed using the structure of the design problem defined above. The design of the means will be treated in the next Section.

Means

After the design of the processors in the control system, the means are designed. Firstly, the input to this design phase will be discussed. Secondly, the design of the structure will be treated. Finally, the design of the elements designed in this design phase will be treated.

Figure 4.16 shows that the input to this design phase is the control processor-diagram. The processors, collected in this diagram, are concretised into means in this design phase. The structure of the means will be similar to the structure designed in the previous phases. Again, for reasons such as cost, data access or data consistency, it may be decided to combine two or more processors into one means.

The elements designed in this design phase are the means. The means are the concretisations of the processors, designed in the previous design phase, and may be human or physical. The human means in the control system is the personnel in the different levels of the system hierarchy. The personnel will be selected in this design phase and instructions for the personnel, based on the processors' design, will be written. The personnel in the control system can be combined with the personnel in the manufacturing system. An operator in the manufacturing system, for instance, can also perform some control tasks. In the control system design process, therefore, attention should be given to the manufacturing system design process.

Physical means will be selected from the existing catalogue of information processing equipment. In some cases, special purpose equipment will be designed, based on the processor design. As well as the selection or design of the hardware, the algorithms designed in the previous design phase will be designed further. An algorithm is the software that is implemented on information processing equipment, the hardware. Attributes like speed, ease of programming and maintainability play an important role in the selection of a programming language for the software development.

The entire software development cycle starts in the process design phase with the design of the process descriptions, the mechanisms. In the second phase, software is concretised in the design of the processor descriptions, the algorithms. The actual implementation of the software – the programming – is done in the final phase of the control system design. Software development has been described in numerous handbooks. A number of the software development methods have been listed above. Here, software development is done in parallel to hardware design.

The result of the means design phase is a control means-diagram, illustrating the means. In the control means-diagram for the toy-car control system, computer systems and personnel are represented according to the control system processor-diagram, shown in Figure 4.23. The control means-diagram can be split into two diagrams: a human control means-diagram and physical control means-diagram. The instructions or task descriptions of the personnel and the listings of software for the hardware complete the control means-diagram.

The control system design process has been described in this Section. Three phases have been discussed. The control system design process can be seen as the parallel design of hardware and software. Physical hardware consists of all information processing equipment. Software for the physical hardware consists of computer programs. Human 'hardware' consists of all personnel in the control system. Software for the personnel consists of the task descriptions and instructions.

Methods and techniques to support decision making in the control system design process can be developed using the structure of the design problems defined above. Supporting techniques for software development already exist for all four steps of the decision cycle.

4.4.4. Conclusion

Relevant attributes and detailed design methods in the design of the four basic sub-systems have been treated in the previous sections. All four steps of the decision cycle need to supported. Methods and techniques supporting analysis, synthesis, evaluation and decision have been discussed for all phases of the industrial system design process.

Many methods and techniques have been developed to support product design. Most techniques focus on the product attributes. Optimisation, modelling and evaluation techniques have been developed in this area. Recently, the relation between product attributes and the attributes of other sub-systems has been studied. This yielded many useful DfX-methods. Most DfX-methods focus on the relation between product and manufacturing system, whilst others attend to the relation of product design to the environment.

Most methods and techniques developed for product design can be used in the concrete phases of the product design process. Recent design research pays more attention to the more abstract design phases. It is expected that methods to support the abstract phases of the product design process will further improve the design processes and object design.

Next, the manufacturing system design process was discussed. Three phases were introduced in Section 4.3.2. Methods and techniques that can be used in all three phases have been treated. It has been shown that most existing techniques are inherently sub-optimal, because too few attributes or too few other sub-systems are taken into account. More research is required to provide more powerful modelling, optimisation and evaluation techniques.

The financial system and the financial control system have not been discussed in this dissertation. The structuring of the financial system and the financial control system design process in principle can be carried out similarly to the structuring of the manufacturing system and the control system respectively.

4.5. Conclusion

The industrial system design process has been discussed in this Chapter. The procedure that has been proposed in Chapter 3 has been used to structure the industrial system design process. Firstly, the definition of the objective was formalised. Next, the division into basic sub-systems was discussed. This discussion introduced basic sub-systems in an industrial system: product, manufacturing system, information system and the financial system. The information consists of the (matter) control system and the financial control system. Thirdly, the phasing of the different design processes has been discussed. The relation of design phases with other phases and other sub-systems was treated. This discussion revealed that sequential execution of design phases is impossible. Figure 4.12 illustrated this for the manufacturing system design process. Fourthly, the attributes that are relevant in the various design phases were covered. Methods and techniques, dealing with the relevant attributes, were examined. These methods and techniques support one or more steps in the decision cycle.

The industrial system design method that is described in this Chapter is summarised in Figure 4.24. It shows the standard division into sub-systems and the standard phasings with the resulting design documents. The four steps in the decision cycle are illustrated in each design phase: (1) Analysis; (2) Synthesis; (3) Evaluation; (4) Decision. In this way, the industrial system design process is modelled as a structured series of design decisions. The theoretical discussion in Chapter 3 showed that other divisions into sub-systems and other phasings can be chosen.

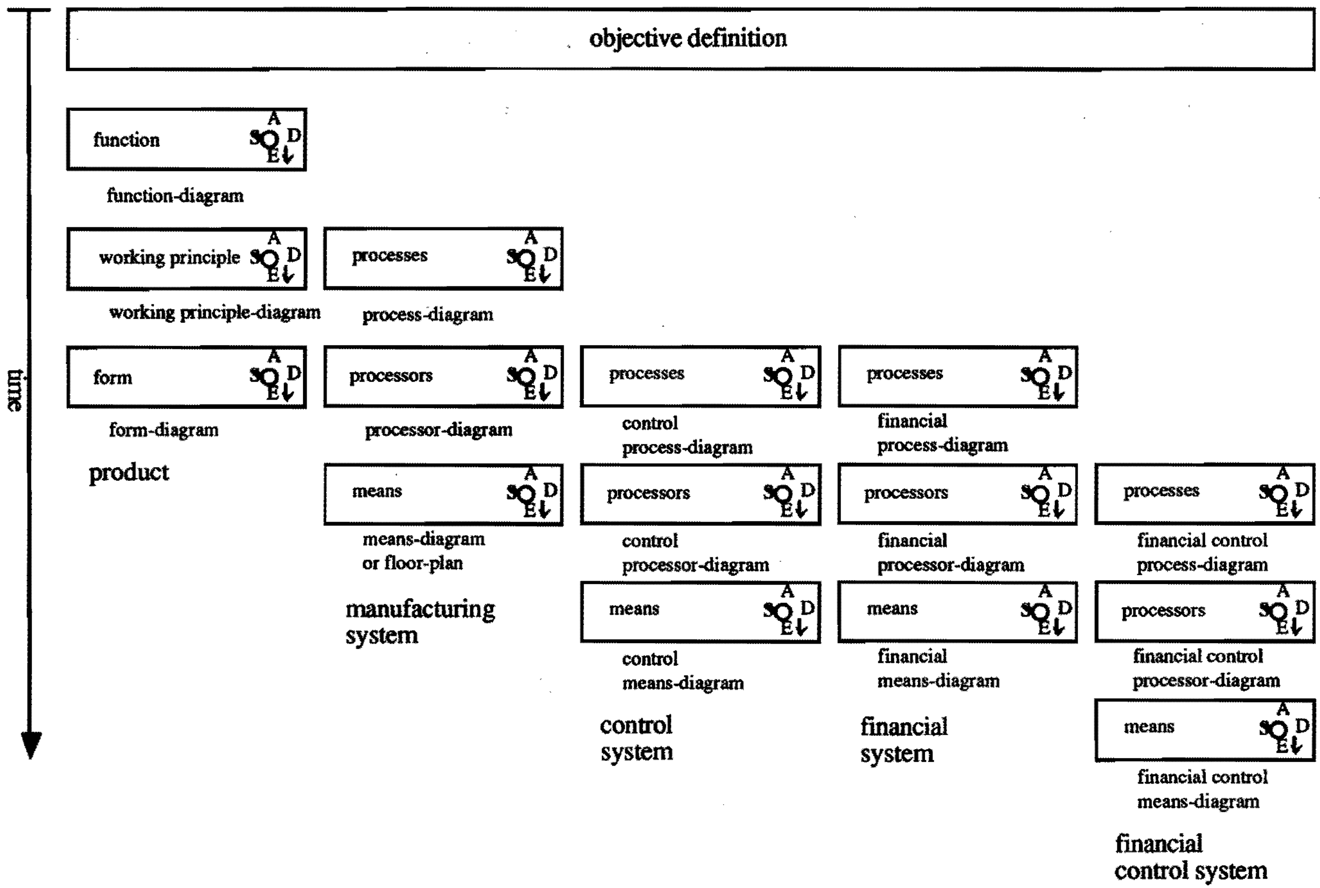


Figure 4.24. The industrial system design process.

The structure represented in Figure 4.24 can be used in the design and redesign of industrial systems. It has already been successfully used in several redesign projects [Van Bree, 1993; Brands, 1993; Sloesen, 1993, Clevers, 1993]. Supporting methods and techniques based on this structure need to be developed to further improve the quality of the design process and the object designs. The basics of these methods have been discussed in this Chapter.

Actual decision-making is still done by the designer. For this, the designer can make use of the decision cycle that has been discussed in Chapter 2. There, decision-making has been modelled as four steps: (1) analysis, (2) synthesis, (3) evaluation and (4) decision. Some existing methods can be used in the structured design methods. These have been discussed in the previous sections. Decision making can then be supported by the deployment of these methods.

The industrial system design process has been discussed in this chapter. In the previous chapter, the feasibility and usefulness has been dealt with. There, structuring of the design process was compared with linearising a chaotic process. The structured industrial system design process is also such a linearisation. This implies that the various steps in the structure, represented in Figure 4.24, cannot be carried out sequentially. Iterations are still an essential part of design; decision-making in the industrial system design process, however, can be made more systematic using the structure represented in Figure 4.24.

An industrial system design method has been discussed above. After the first research objective, the second research objective that has been stated in Chapter 1 has now also been achieved. The validity and quality of the method, however, still remains unclear. The third research objective, therefore, needs to be achieved as well. The alleged positive influence of structured design needs to be tested, and for that, an empirical test of the method is necessary. The next Chapter will discuss the empirical testing of the structured design method presented in this Chapter. After this, Chapter 6 will present an elaborated illustration of the industrial system design method.

Chapter 5

Empirical Test of Structured Design

A structured approach to the design process has been presented in Chapter 3. This approach can be elaborated for different object designs. In Chapter 4, the structured industrial system design process was discussed. This structure will be compared with intuitive design in Chapter 6 with an example from the real world. In addition to this, the structure has already been applied in some industrial cases. This, however, is no proof of the validity of the proposed structure. The sample space size is too small. Therefore, an empirical test is necessary.

An empirical test of a design method would require several designers and several design problems. The group designers would be divided into groups having different levels of experience. Various design problems, classified into different classes, would have to be used. Then, each designer would tackle a particular design problem and results would have to be evaluated. Since, however, industrial system design processes generally take at least several days, getting a representative sample would require years of intensive and expensive research. Nevertheless, interesting insights can be obtained with a small empirical test. Such a test of the structured manufacturing system design process will be discussed in this Chapter.

Firstly, the hypotheses that will be tested will be described. Secondly, the experimental design will be treated. Thirdly, the results of the empirical test will be presented and discussed. Finally, some conclusions will be given.

5.1. Hypotheses

It was stated in Chapter 2 that research on the structured design process would lead to better design results. It will be shown in Chapter 6 that a structured approach can be used to design and redesign an industrial system. This structured approach revealed design decisions that are usually made unconsciously. It, however, remains uncertain whether the structured approach leads to better results than the conventional, more improvising approach. Is the design of the design process useful? To find this out, some empirical research is required. The basic question in this experiment is whether designers can be guided such that they perform differently to conventional, non-guided, designers.

It is desirable that designers address the fundamental design issues and that their attention is not directed exclusively to concrete design issues. Earlier empirical testing in design research revealed that designers tend to spend very little time in the early, abstract phases of the design process [Stauffer et al., 1987]. Line 1 in Figure 5.1 illustrates this tendency. The most relevant design decisions, however, are taken in these early design phases, see Figure 5.2. The question now is whether a designer can be guided such that he behaves more like line 2 in Figure 5.1. By doing so, he spends more time addressing the fundamental design issues and is more likely to arrive at a better solution.

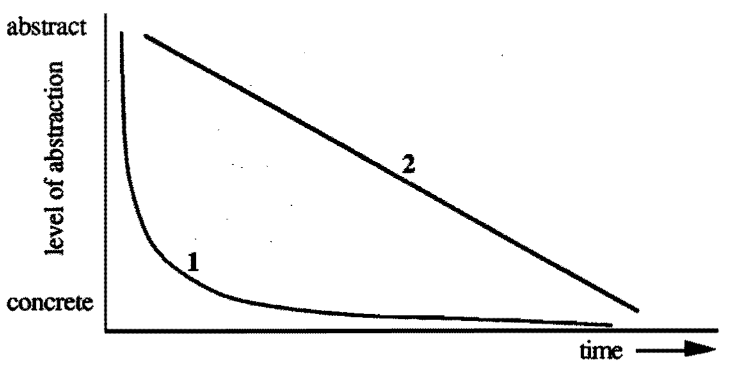


Figure 5.1. Different approaches to the design process.

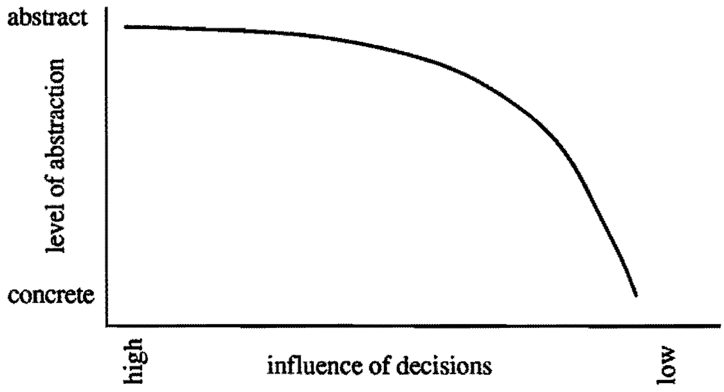


Figure 5.2. The relation between level of abstraction and the influence of decisions.

Two hypotheses, therefore, will be tested:

Hypothesis 1: a designer using the structured design approach described in Chapter 4 of this dissertation will make better design decisions than a conventional designer.

Hypothesis 2: a designer using the structured design approach described in Chapter 4 of this dissertation will address more abstract design problems than a conventional designer.

The experimental design that is set up to test these hypotheses, will be described in the next Section. Following that, the results of the experiment will be discussed.

5.2. Experimental Design

To test the hypotheses, mentioned in the previous Section, two groups of students were used. Each group of 8 students was randomly selected from a group of 16. Nearly all students were in the third year of their studies in Mechanical Engineering, masters level. Differences in foreknowledge will be discussed in the Section on the results. The experiment consisted of two parts. The first part on the first day was an instruction part. The second part on the second day was the design part. These will be discussed in turn.

Firstly, some general instructions were given to all 16 students, see appendix B. Then, the two groups were selected randomly. The two groups were split up and received two different lectures. Group A received a lecture on the structured design approach as described in Chapter 4, whereas group B received a repetition of the lectures received earlier in their curriculum. The two lectures will be briefly described.

The lecture given to group A was based on two articles [Brandts, 1993a; Brandts, 1993b]. The design process in general is discussed in the first article. The design cube is introduced and the division of the three axes is discussed. The design process of industrial systems is discussed in the second article. The division of an industrial system into basic sub-systems is discussed. Then, the phasing of the manufacturing system design process is discussed in more detail. Design documents are proposed for the three phases of the manufacturing system design process: the process-diagram, the processor-diagram and the floor-plan. The three design phases are treated, discussing the input from other design phases and the attention that should be given to other design phases and to other sub-systems. No methods to make design decisions in the three phases were discussed in any detail. In other words, only the structured approach was treated.

The lecture given to group B was based on lecture notes by Renders [1988]. Instruments to analyse and redesign manufacturing systems were discussed in this lecture. It was a repetition of a lecture received earlier in the curriculum. The students in group A also have received this lecture earlier in their curriculum. The lecture discussed (re-) design methods in some detail. All phases of the design process are covered by the design documents discussed in the lecture, representing an up-to-date view of manufacturing system design. Differences between the two groups lay in the structure given to group A and the more detailed design methods given to group B.

The lecture lasted from 9.30 am to 12.30 pm. After lunch, all students were given the opportunity to study the material given to them in the lectures and the material presented earlier in their curriculum. Appendix B lists the literature that could be studied. The afternoon session was finished at 4.30 pm. The students were sent home and asked not to communicate on the subject.

The second day started at 9.00 am with a repetition of the instructions, see appendix B. The designers were asked to write down their thoughts as complete as possible. The design problem was distributed at 9.15 am. This is presented in appendix B. All 16 students individually redesigned the factory described in the assignment. Questions could be submitted in writing. Every half hour, the time was announced. The students were asked to write down the time in the left margin. In this way, it was possible to follow the designer in the design process. Lunch was from 12.30 pm to 1.30 pm. It was ensured that the designers did not communicate on the design problem. Redesign restarted at 1.30 pm and lasted until 4.30 pm. Then, the designers were asked to give some remarks on the lecture they had received, the method they had followed, the assignment and their foreknowledge of the subject where this might have deviated from the normal Mechanical Engineering curriculum. Finally, all drawings, calculations, notes and remarks were collected.

5.3. Results

All drawings, calculations and notes were collected at the end of the design session. This resulted in 16 piles of paper to be studied. The results were quite dissimilar. Results did not only differ in quality, as might be expected, but also in the degree to which thoughts and considerations were written down. The latter makes it impossible to compare, for instance, the number of iterations between the two groups. Notes were too brief to track the thoughts of the designer. Nevertheless, the notes were sufficiently complete to reveal the designer's broad behaviour.

Testing the First Hypothesis

Firstly, the first hypothesis will be tested. Three different people, familiar with the design problem and marking were asked to assess the result of the 16 designers. Their marks are presented in Table 5.1. The three marks are averaged and the average is also listed in Table 5.1. No clear differences can be found between the two groups. On average, group A scores 3 % higher than group B. A Student t-test shows, with a certainty of 99.95%, that the difference between both groups is not significant. The first hypothesis, therefore, cannot be accepted.

Table 5.1a. Marks for group A

Designer	1	2	3	μ
A1	7	5	6	6
A2	5	7	6.5	6.17
A3	6	5	6.5	5.83
A4	3	6	6	5
A5	8	9	6.5	7.83
A6	4	6	6	5.33
A7	4	8	6.5	6.17
A8	5	5	7.5	5.83
Total μ	5.25	6.38	6.44	6.02

Table 5.1b. Marks for group B

Designer	1	2	3	μ
B1	3	5	6	4.67
B2	5	5	6	5.33
B3	5	7	6.5	6.17
B4	2	6	6	4.67
B5	6	9	7.5	7.5
B6	5	7	7	6.33
B7	7	5	5.5	5.83
B8	5	7	7	6.33
Total μ	4.75	6.38	6.44	5.85

This can be explained. Knowledge and experience of the designers in both groups are equal. Group A had received a lecture in the structure of the industrial system design process. No design methods or knowledge on the making of specific design decisions were dealt with. In other words, their decision-making was only structured. Group B had received a refresher course, in which a number of more detailed design methods, treated earlier in their curriculum, were dealt with. The designers in group A also have or should have this knowledge. Marks were awarded to designers without considering that the design of a new production structure is perhaps preferable above the design of a new floor plan. The results show that the designers of groups A and B score equally well. It should be pointed out that results are difficult to compare, because the designers in the different groups addressed different design problems.

Testing the Second Hypothesis

Next, the second hypothesis will be tested. It was seen that the 16 designers together addressed five different design problems. These were: (1) process selection, (2) design of production structure, (3) adaptation of production capacity, (4) machine allocation, and (5) design of the floor-plan. The five design problems are listed according to the level of abstraction in the design process. Process selection is a more abstract design problem than machine capacity, and machine allocation is less abstract than the design of a production structure. A first impression of the differences can be obtained by studying the design problems that were addressed. After this, a more detailed view can be obtained by investigating the amount of time spent with the various design problems. Table 5.2 shows the design problems addressed by groups A and B. It shows, for example, that 50 % of the designers in group A addressed the process selection problem, whereas only 12.5 % of group B did so. The differences between the two groups are apparent. Group A has addressed more abstract design problems than group B.

Table 5.2. Subjects addressed by group A and B.

subjects	group A	group B
process selection	50.0 %	12.5 %
production structure	87.5 %	25.0 %
machine capacity	87.5 %	50.0 %
machine allocation	12.5 %	50.0 %
floor plan	37.5 %	87.5 %

This too can be explained. Both groups are confronted with an actual factory, i.e. a concrete system. The designers in group B used the methods to make adaptations to the concrete manufacturing system. The designers in group B, therefore, were directed by the existing manufacturing system. Consequently, concrete design problems were addressed. The designers in group A, however, were directed by the existing manufacturing system as well as the structured design approach. Since no other relevant differences could be found between the two groups, the structured design approach must have been responsible.

A more detailed way to test the second hypothesis is to study the designer's behaviour in time. Notes are too brief to precisely track the thoughts of the designer. They are, however, complete enough to study the course of the subjects treated in the design process. A distinction is made between the analysis and the making of design decisions. Again, the same five subjects mentioned above are used. Besides these five subjects, three other subjects to indicate the designer's activity are added: (1) product analysis, (2) general remarks, (3) no remarks. Figures 5.4a and 5.4 b show the behaviour of two particular designers in the design process. The behaviour in time of all 16 designers is included in appendix B. Figure 5.3 shows the legend to Figure 5.4a and 5.4b.

1. products
2. process
3. production structure
4. production capacity
5. machine allocation
6. floor plan
7. general remarks
8. no remarks

Figure 5.3. Legend to Figures 5.4a and 5.4b.

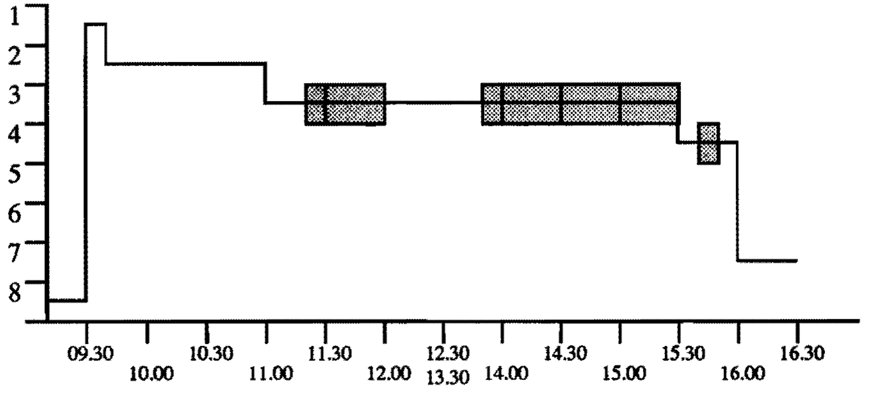


Figure 5.4a. Behaviour in time of typical designer in group A.

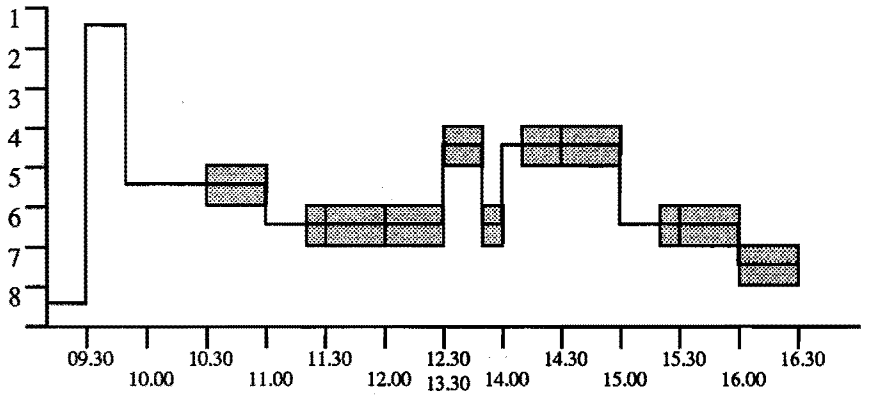


Figure 5.4b. Behaviour in time of typical designer in group B.

Many things can be deduced from Figures 5.4a, 5.4b and the other figures in appendix B. Firstly, it can be seen that the designers in group A addressed more abstract design problems than the designers in group B. This is a confirmation of the second hypothesis. The time spent by all designers of a particular group is totalled and the results are shown in Figures 5.5 and 5.6.

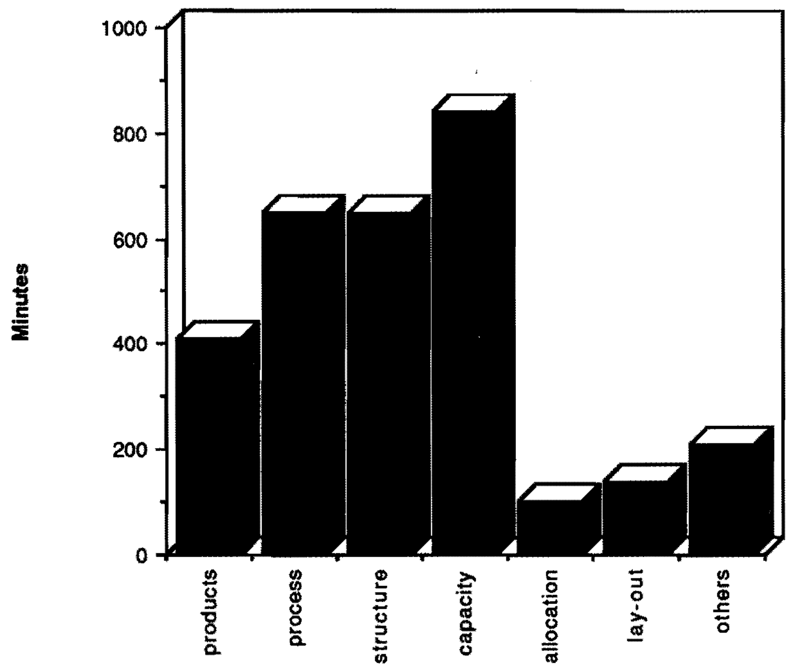


Figure 5.5. Total time spent on various subjects by group A.

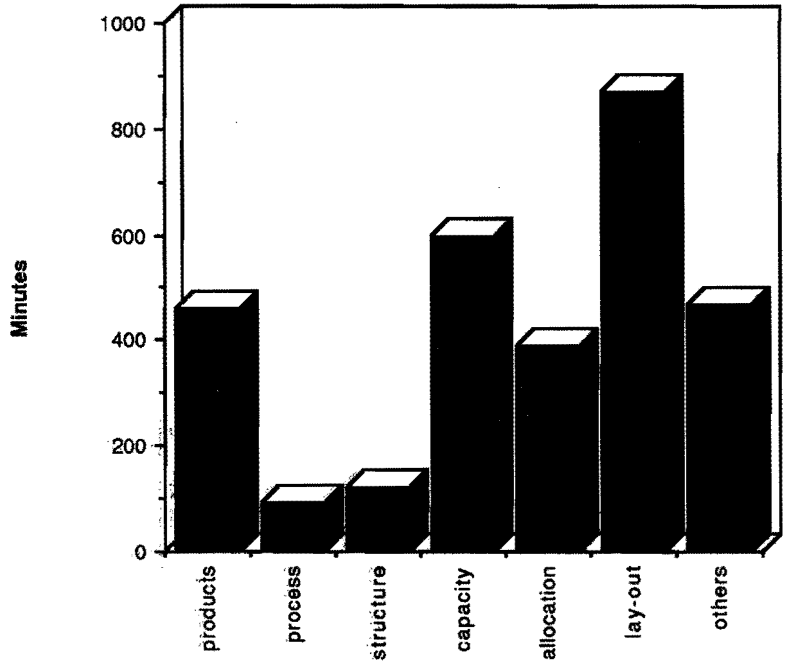


Figure 5.6. Total time spent on various subjects by group B.

Figure 5.5 and 5.6 show the total time spent by each group on the various design problems. The differences between the two groups are obvious, the most striking being the time spent in process selection. Group A spent more than seven times as much time in process selection than did group B. Table 5.3 shows the differences in time spent between the two groups. If the remarks made by the designers on the continuation of their design process, were used to extrapolate Figures 5.5 and 5.6, differences would become even more apparent.

Table 5.3. Time spent with the various design problems (design and analysis).

	Group A	Group B	Difference	
process selection	21.7 %	3.0 %	7.2	
production structure	21.7 %	4.0 %	5.4	
machine capacity	28.0 %	20.0 %	1.4	
machine allocation	3.3 %	13.0 %		3.9
floor plan	4.7 %	29.0 %		6.2

Both analysis and design are taken into account in Table 5.3. If only design is taken into account, Table 5.4 results. Although Table 5.3 differs from Table 5.4, results are similar. The designers in group A have spent more time in the abstract design phases than have the designers in group B. The results of the experiment support the second hypothesis.

Table 5.4. Time spent with the various design problems (design only).

	Group A	Group B	Difference
process selection	16.2 %	3.0 %	5.4
production structure	41.9 %	11.1 %	3.8
machine capacity	30.8 %	24.2 %	1.3
machine allocation	3.4 %	22.2 %	6.5
floor plan	7.7 %	38.4 %	5.1

Other subjects that might have been studied were: the number of iterations, the number of criteria taken into account and the attention that has been given to other subsystems. Notes, however, were too brief to reveal detailed information on these subjects. The number of iterations that can be tracked in both groups does not essentially differ. It could be seen that the number of criteria used is somewhat larger in group A than in group B. Other subsystems are considered more often in group A than in group B. Products are mentioned equally often in both groups, the control system is often mentioned in group A and remains undiscussed in group B.

5.4. Discussion

The results of the experiment showed that the first hypothesis cannot be accepted, whereas the second hypothesis can be accepted. The quality of the design decisions, in other words, does not essentially differ. The designers do address different design problems. There is, however, a correlation between the two hypotheses. This relation is given in Figure 5.2. It shows that the more abstract design problems have more influence on the final object design than more concrete design problems.

More empirical research is necessary to test the first hypothesis. The prove of this, however, is complicated by the fact that the quality of the object design is a so-called *bottom-line variable* [Van Aken, 1993]. This implies that many interrelated aspects need to studied. The benefit of designing the design process is based on the assumption that designers can be guided towards strategic design problems. The test discussed here showed some evidence of this. Many other variables, however, are involved in the making of design decisions, making the proof of the first hypothesis extremely difficult.

Another observation that can be made studying Figures 5.4a, Figure 5.4b and the related figures in appendix B, is that the designers in group A nearly all were not able to finish the design process. Continuation of the design process would have led to the addressing of more concrete design problems. In their remarks, designers in group A mentioned the continuation of the design process towards more concrete design problems. This is in accordance with the structured design approach. The designers in group B all mentioned the further optimisation of the concrete design problems they already addressed. Two things can be derived from these observations. The structured design approach will lead to manufacturing systems where all levels of abstraction are addressed and optimised, and on the other hand will lead to a slower design process, because more design problems are addressed.

5.5. Conclusion

The structured design approach has been tested empirically in this Chapter. This way of design research reveals interesting information on the quality of design methods. It is the only way, in fact, in which this can be tested, since theoretical deduction at the moment is impossible. Therefore, empirical research should be applied more often.

The small empirical test that has been presented in this Chapter, has compared the structured design approach discussed in Chapter 4 with the conventional design approach as used in the department of Mechanical Engineering at Eindhoven University of Technology. The first hypothesis that stated that the quality of design decisions would differ was not supported by the results. The design problems, however, addressed by both groups were very different. The designers in group A, who used the structured design approach, addressed more abstract problems than those in group B. This lends support to the second hypothesis.

Further conclusions can be drawn after examination of the results. The designers in group A used more criteria than the designers in group B to make their design decisions. Designers in group A paid more attention to the control system than did the designers in group B. The designers in group A, in other words, have made their decisions with somewhat more consideration than have the designers in group B. Again, it is stated that notes are too brief to make precise statements on this subject.

This experiment shows that the deployment of the structured design approach is recommendable, because the more abstract design phases receive more attention. It is believed that this will have a positive influence on the quality of the object design. As a consequence, the design process will evolve more slowly, because the more abstract phases are not rushed through. It is expected that these effects will also be observed in the design of a new manufacturing system. The third research objective mentioned in Chapter 1 has partially been achieved. More empirical research is necessary to prove that structured design always has positive effects on the quality of the design process and the object design.

More research is necessary to validate the structured approach. Designers with different levels of experience should be used. The sample size should be increased. The designers should be made familiar with protocol analysis [Ericsson & Simon, 1984; Ennis, Gyeszly, 1991]. The designers are asked to express all of their thoughts. By doing so, the design process will be easier to track and more knowledge will be gained. Different manufacturing systems should be taken for redesign. The influence of groups of designers can be studied. As well as redesign, the design of new manufacturing systems should be studied. After the study of the manufacturing system design process, the entire industrial system design process needs to be studied. Besides this, design methods that can be used in structured design require empirical testing.
By integrating empirical research into design research, design research can be made more scientific than it is today.

Chapter 6

Illustration of Structured Design

In the previous Chapters, the structuring of design processes has been discussed. Chapter 3 treated the theory on the structuring of design processes. The structuring of the industrial system design process was discussed in Chapter 4. A method for the structured design of industrial systems was presented. Relations of the design processes of basic sub-systems with other basic sub-systems were examined. Chapter 5 then looked at the empirical testing of structured design. This revealed that the use of a more structured approach should lead to better object designs, because it addresses the more fundamental problems.

The benefits of structured design will be illustrated with a realistic example in this Chapter. The objective in this Chapter, however, is not to redesign the industrial system, but to illustrate structured design and to compare structured design with intuitive design. Structured design will be used to trace the design process in different periods of a particular industrial system. Design decisions taken intuitively are placed in the design method, so that intuitive and unconscious design decisions are revealed. Suggestions for optimisation can be given using structured design, but, in this Chapter, only some minor suggestions will be given, since the objective of this exercise is to compare structured design with intuitive design and not to produce a better object design.

In addition to this, decision making in the different periods will be studied. This will reveal the influence of a changing environment on the industrial system and its design process. The procedure that has been proposed for the definition of the objective will be used to investigate this changing environment. The rest of the industrial system design process will be described using the structure that has been proposed in Chapter 4. All design

decisions, taken intuitively, are placed in the structure. By doing so, intuitive decision making can be compared with structured design.
The industrial system studied in this Chapter is a rubber processing company whose customers can be found in the automotive industry. In the rest of this Chapter, the production system will be called PL. PL will briefly be introduced in Section 6.1.

The rest of the Chapter is organised as following. Firstly, the industrial system is presented in Section 6.1. Next, structured design will be used to study the industrial system design process in four different time periods. Objective definition, product and production system design will be treated for all periods, starting with the initial situation that existed in the seventies and eighties. Design decisions that were made in this period will be discussed in Section 6.2. Following this, the situation in the early nineties will be discussed. The changing environment had forced a redesign in this period. Design decisions that were made in the reorganisation will be discussed in Section 6.3. Then, the current situation will be discussed in Section 6.4. The iterations that were necessary after the reorganisation will be treated. Finally, in Section 6.5, future developments will be treated using structured design. The Chapter will be completed in Section 6.6 with conclusions and a summary of all possible improvements in the industrial system.

A more extensive treatment of the data used in this Chapter can be found in Clevers [1993] and Sloesen [1993]. In this Chapter, a high degree of modelling abstraction is used, implying that not all the available data is presented. The essential elements of the design process, however, will be treated.

6.1. The PL Industrial System

Structured design will be illustrated with a realistic example in this Chapter. For this, an industrial system has been chosen: PL. PL will briefly be introduced in this Section. Some key figures will be used to illustrate the size and complexity of the products and the production system. A more extensive discussion is given in the next Sections.

The production system discussed in this Chapter is a rubber processing company. All products, therefore, contain at least one rubber component. Different product types are produced. Important product types are the Water-Pump Seals (WPS) and the Shock

Absorber Seals (SAS's). Besides these product types, numerous other rubber products are made. Here, only the SAS's and the SAS production system will be considered. Figure 6.1 presents a technical drawing of a general SAS.

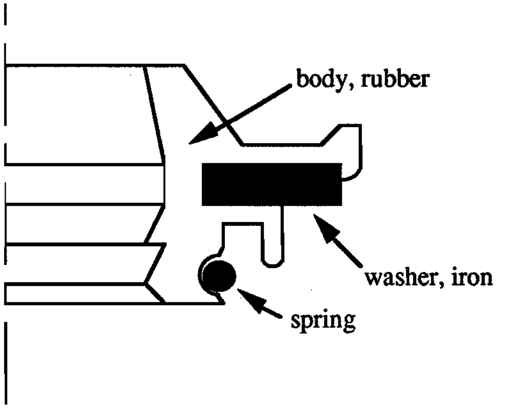


Figure 6.1. Technical drawing of a general SAS.

In 1992, the turnover was 34 million guilders. 9 million (26.5 %) of the turnover was created by the sales of SAS's. A total of 200 people finds work in PL. 55 (27.5 %) of these are involved in the production of SAS's.

The SAS production system produced over 12.3 million SAS's in 39 different types in 1992. This is equivalent to a 15 % market share in Western Europe. Most customers of PL can be found in the automotive industry. The tendency in automotive production to decrease lead times and prices [Womack et al., 1991] has led to many problems in the supplying production systems. This will be shown in Sections 6.3 and 6.4.

Four different time periods in the history of the PL industrial system will be discussed: the initial situation that existed in the seventies and eighties, the first redesign project in the early nineties, the current situation and the future.

6.2. The First Period: the Initial Situation

Structured design, discussed in Chapter 4, is illustrated in this Chapter. Four different periods in the history of PL will be treated. The initial situation will be discussed in this Section. This situation existed from the early seventies until the late eighties. The changes that were necessary after this period will be discussed in Section 6.3. The design process for the initial situation will be treated using structured design. By doing so, design decisions will become manifest. The different steps in structured design will be treated consecutively.

6.2.1. PL Objective Definition in the First Period

The first step in the industrial system design process involves the definition of the objective. A procedure for the objective definition has been proposed in Section 4.1. This procedure will be used in this Section to structure the objective definition for PL in the initial situation.

The procedure for objective definition described in Section 4.1, consists of three steps. The Interested External Systems (IES's) are identified in the first step. The relevant attributes are identified in the second step. Finally, the attributes are weighed in the third step. The first two steps have been executed for a general industrial system in Section 4.1. The findings for this general industrial system will be used for PL in this Chapter.

Seven IES's have been identified: (1) matter suppliers, (2) matter consumers (customers), (3) energy suppliers (financiers), (4) labour market, (5) equipment suppliers, (6) equipment consumers (demolition firms) and (7) government. Table 4.1 shows a collection of relevant attributes related to the seven IES's.

The relevant attributes need to be weighed for PL in the third step. The equipment suppliers and equipment consumers are left out of the weighing process as they are less relevant. Government is also omitted, because governmental attributes are hard constraints that always need to be satisfied. Four IES's remain: (1) matter suppliers (suppliers), (2) customers, (3) financiers and (4) labour market. The relevant attributes of the four remaining IES's can be derived from Table 4.1 and are listed in Table 6.1.

Table 6.1. The relevant attributes of the IES's of PL.

IES	Relevant attributes
suppliers	functionality / quality price delivery time amount
customers	functionality / quality price delivery time amount
financiers	return on investment
labour market	salary job satisfaction

Next, the relevant attributes of the four IES's will be treated per IES. Here, the initial situation will be treated. Table 6.1 will be used for the other time periods in Sections 6.3 to 6.5.

Suppliers

The objective attributes of the suppliers will be treated in this Section. Four relevant attributes have been identified for the suppliers. In the initial situation, most attention was paid to material and products of sufficient quality at a low price. The delivery times were of less importance, because the delivery times PL's customers asked were long. Changes in the environment towards the end of this first period forced the suppliers to adapt their production system. This will be treated in the Section dealing with the early nineties.

Customers

The requirements for the product design process are set in the objective definition phase. In most cases, only a few attributes are set. The rest of the design process involves design decision making concerning the functions, working principles and eventually form. The customer, however, may also prescribe the attributes to a greater degree of detail. In those cases, the objective definition phase is larger than the rest of the design process.

Two situations can be distinguished in the PL product design process. Firstly, customers may offer a detailed technical drawing of the SAS in which all design decisions have been taken. Then, objective definition involves the entire product design process. Secondly, customers may offer a technical drawing in which nearly all design decisions have been taken. Some design decisions, like material choice and some geometrical attributes, are, though largely constrained, yet to be taken. Figure 6.2 shows the two possible variants of the PL product design process. Although PL's expertise is used by customers to determine the product attributes, Figure 6.2 is a good representation of past, present and future product design. In all periods, 50 % of all product types was designed using the first approach and another 50 % was designed using the second approach.

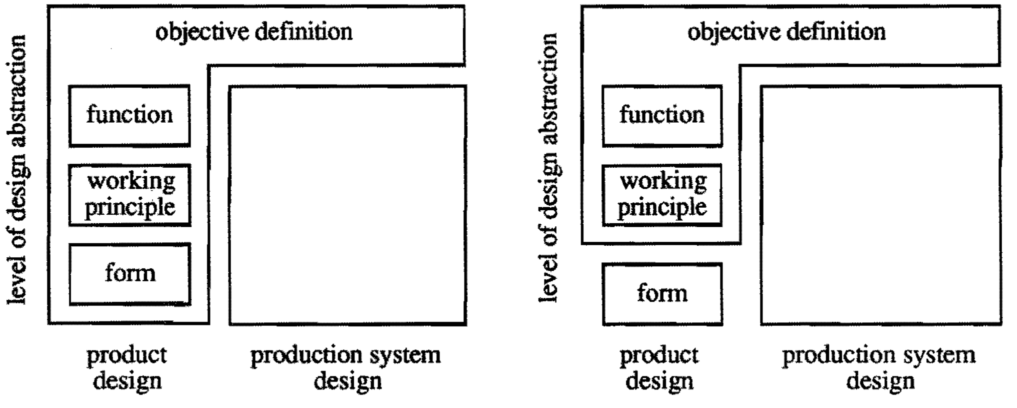


Figure 6.2. Two possible approaches to PL objective definition and product design.

The relevant attributes of customer requirements will be treated next. Firstly, functionality and quality will be treated. Secondly, prices will be discussed. Next, delivery times will be discussed and, finally, the amounts will be treated.

Customers' requirements of a product's functionality and quality have been stable in the first period. For some two decades these requirements have not substantially changed. Requirements, however, became more strict towards the end of the first period. This will be discussed in the Section on the second period. Requirements on SAS involved the ability to resist an aggressive environment and a minimum life span of one year. The influence of PL product designers on the product design, however, is limited to the concrete design phases.

SAS prices roughly followed inflation levels in the first period. A gradual increase of prices, therefore, can be observed.
The delivery time demanded by the customers was approximately 12 weeks in the initial period. At the end of this period, changes in the customer requirements were observed. These will be treated in the next Section, dealing with the situation in the early nineties.

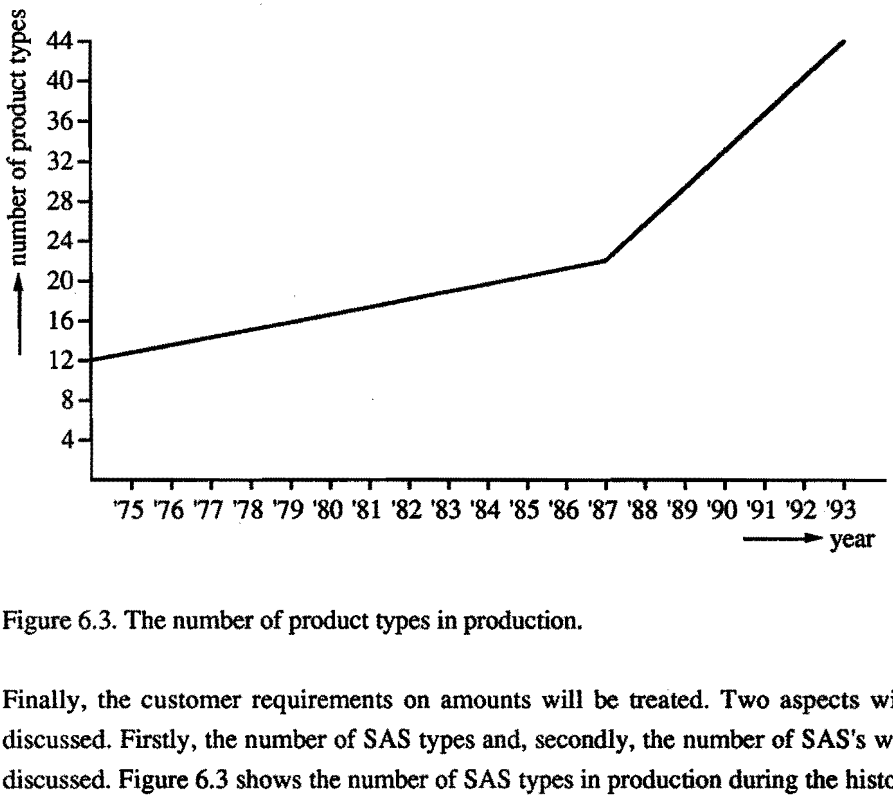


Figure 6.3. The number of product types in production.

Finally, the customer requirements on amounts will be treated. Two aspects will be discussed. Firstly, the number of SAS types and, secondly, the number of SAS's will be discussed. Figure 6.3 shows the number of SAS types in production during the history of PL. It can be seen that the number of product types was relatively constant and showed a sharp increase towards the second period. This will be treated in more detail in the discussion on the second period. Figure 6.4 shows a cumulative Product-Quantity diagram (or Pareto-diagram) [Balkestein et al., 1987], showing the relation between the product types and the number of products demanded. The form of Figure 6.4 has been stable throughout the history of PL.

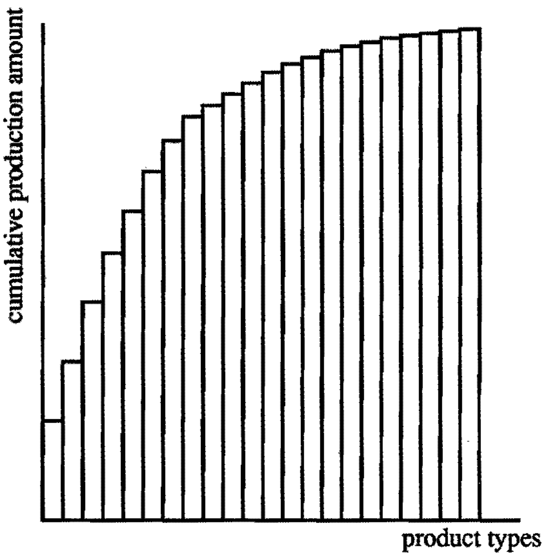


Figure 6.4. The cumulative Product-Quantity diagram.

Figure 6.5 shows the number of SAS's sold. A relatively stable situation can be observed in the early years, whereas sales have grown considerably towards the end of the initial period. The Section on the second period will discuss this phenomenon in more detail.

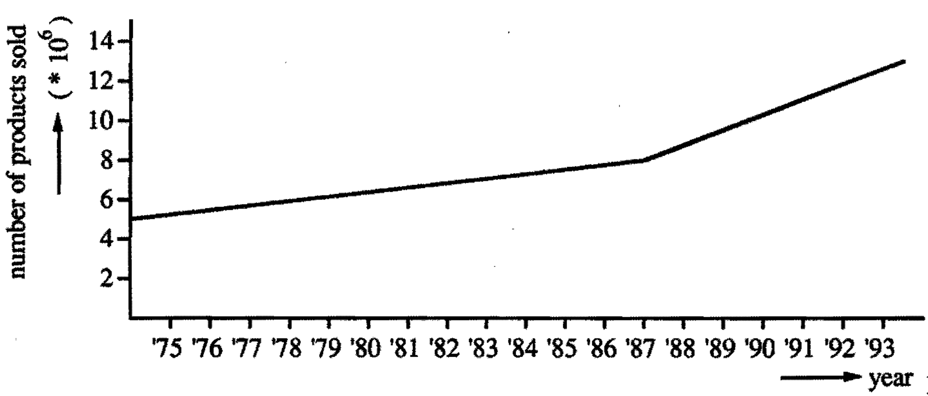


Figure 6.5. The number of SAS's sold.

Financiers

Thirdly, the financiers will be treated. The attribute of the financiers studied in this case is the return on investment (ROI). The financiers' requirement ROI differs for different investments. Besides this, the ROI changes in time. Here, the ROI is considered to be constant in time and for different investments. The expected ROI is taken to be 12 %.

Labour Market

Finally, the labour market will be treated. Two objective attributes have been mentioned for the labour market: salary and job satisfaction. The developments in salary have followed inflation. The requirements on job satisfaction have been stable in the initial period. High unemployment resulted in a lower requirement for job satisfaction.

Weighing of the Attributes

The different objective attributes have been discussed in the previous Sections for the initial situation. Table 6.2 shows the weighing of the different IES's and their relevant objective attributes [Boshuisen, 1993]. The higher an objective attribute is represented in Table 6.2, the more important it was judged by PL management. It judged the SAS functionality and quality, together with the SAS price, as the prime criteria for the design of the PL industrial system. This resulted in the industrial system that will be discussed in the following Sections. The changing environment and the necessary reconsideration of the objective attribute weighing will be treated in the Sections on the redesign of the PL industrial system.

Table 6.2. Weighing of the objective attributes.

Customers functionality (quality)
Financiers Return on Investment
Customers price delivery time
Personnel salary working conditions
Suppliers all objective attributes

Conclusion

The definition of the objective for the PL industrial system has been discussed in this Section. Customers pre-determine most of the product design. The product design process, therefore, is almost entirely part of the objective definition phase. The requirements on the different objective attributes have been relatively stable in the initial period. Towards the end of this period, customers had become more demanding. This will be treated in the Section on the second period.

After the discussion of the objective definition, the products and the product design process will be treated. It has been shown that most of the product design process is part of the objective definition. The rest of the SAS design process will be treated in the next Section.

6.2.2. PL Product Design in the First Period

The definition of the objective has been discussed in the previous Section. The next step in structured design involves the design of the products. The products of PL and the design of those products will be treated in this Section. Most of the product design process with PL is part of the objective definition phase. The rest of the design process, discussed in this Section, involves the form phase. In this phase, details of the product object design are filled in. Definitive material choices are made, and final decisions are taken concerning geometrical attributes. The product structure, however, has been determined in the previous working principle phase and remains unchanged.

Firstly, the SAS will be introduced. Figure 6.1 shows a general SAS in which all components are collected. SAS types consist of a rubber part and an iron part. PL product designers have had discussions with customers to translate customer's wishes into SAS details.

The form product diagram that results from the product design process is shown in Figure 6.6. This will be used in the next Section for the design of the manufacturing system. The relation between product-diagrams and the manufacturing system design process has been treated in Section 4.4.1 and 4.4.2.

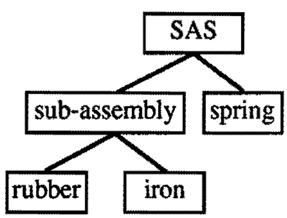


Figure 6.6. Form product-diagram of the SAS.

The number of new products designed in the first period can be derived from Figure 6.3. It can be seen that production in this period has been stable, since the number of new products in production was low. The changes that can be observed towards the end of the first period will be discussed in the Section on the second period.

6.2.3. PL Manufacturing System Design in the First Period

The definition of the objective and the product design process has been discussed for the first period in the previous Sections. The next step in structured design involves the design of the manufacturing system. A division into three phases has been proposed in Chapter 4. It has been shown that in many cases designers are inclined to focus on concrete design phases. This can also be observed in this case. Most decisions have been made on a low level of design abstraction, with little attention paid particularly to the second level. After the appropriate processes were chosen, suitable means were selected or developed. Little attention was paid to the design of the production structure. The design of the manufacturing system will be traced as if it were done using structured design, starting with the processes.

Processes

The first phase in the manufacturing system design process involves the design of the processes. The design of the processes in the first period will be treated in this Section. Figure 6.7 shows a global process-diagram for a general SAS. It can be observed that the manufacturing system processes can be split into preparation processes and finishing processes. Figure 6.8 shows the preparation processes for the iron part of the SAS, whereas Figure 6.9 shows the rubber preparation processes. Figure 6.10 shows some variants of the process-diagram of the finishing processes.

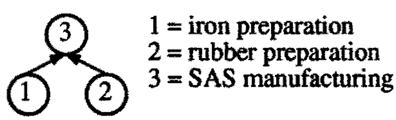
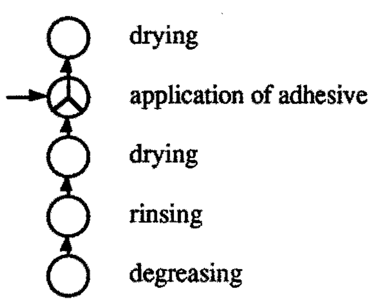


Figure 6.7. General process-diagram.



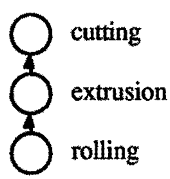


Figure 6.8. Iron preparation process-diagram.

Figure 6.9. Rubber preparation process-diagram.

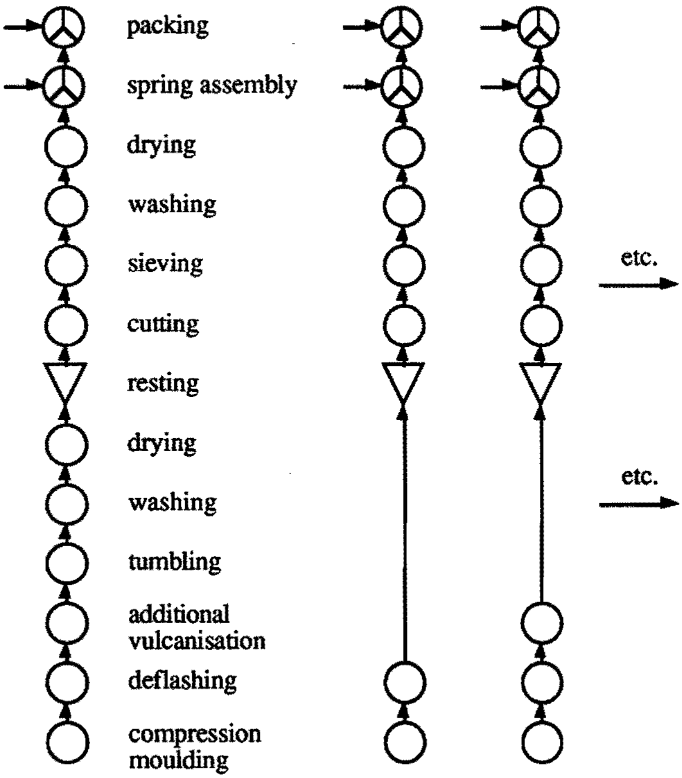


Figure 6.10. Variants of SAS manufacturing process-diagrams.

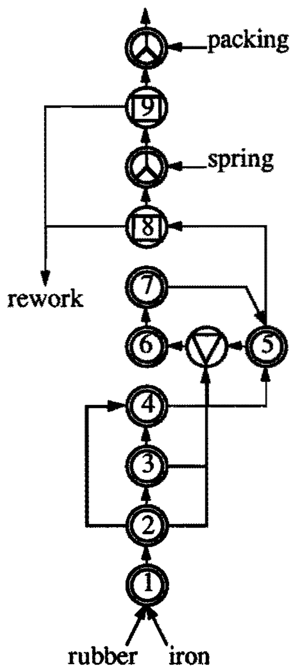
Reasons to select these processes have been quality and price. For some processes no real alternatives existed. Some key processes will be treated in more detail. Different possibilities exist for the vulcanisation and forming of the rubber part. Three processes can be qualified for selection: transfer moulding, compression moulding and injection moulding. The quality of the latter process in the first period was too low, leaving just transfer and compression moulding. Transfer moulding is more expensive than compression moulding, but it is more suitable for intricate shapes [Kalpakijan, 1991]. The forming and vulcanisation of SAS's in the PL manufacturing system is done using compression moulding.

In the initial period, an average of 15 different product types was in production. Variants of the process-diagrams, which differ only slightly, are shown in figure 6.10. These will be combined into a single processor-diagram during the subsequent design phase, as discussed in the next Section.

Processors

After the design of the processes, the processors are designed in the second phase of the manufacturing system design process. The processes are concretised into processors and the structure of the manufacturing system is determined. Paragraph 4.3.2 showed that the design of the processor-diagram involves the addition of extra processes and the concretisation of the structure. Here, the design of the structure will be dealt with first, followed by the concretisation of essential and extra processes.

The design of the manufacturing system structure will first be discussed. The result of this design phase can be visualised in the processor-diagram. An interim result, representing the structure of the manufacturing system, is the production structure, defined in Section 4.3.2. Figure 6.11 shows the production structure of the manufacturing system in the first period. Figure 6.12 shows the incidence matrix representation of this production structure. The structure in the initial situation is a flow of parallel shops with some back-flow.



1 = compression moulding presses (8)
2 = deflashers (homeworkers)
3 = additional vulcanisation ovens (4)
4 = tumblers (3)
5 = washing/drying machines (2)
6 = cutters (8)
7 = sieves (2)
8 = visual inspectors, 100% of products (homeworkers)
9 = end-inspectors, sample survey

Figure 6.11. Production structure of the SAS manufacturing system in the initial period.

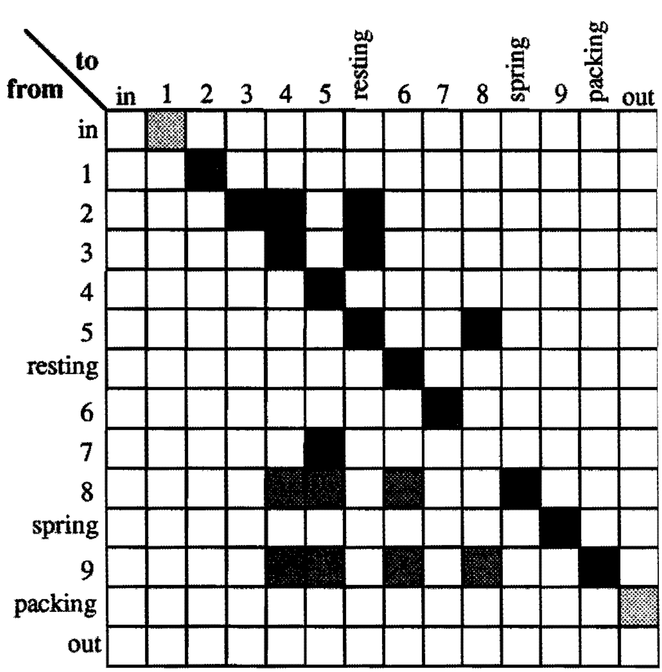


Figure 6.12. Incidence matrix representation of the production structure of the SAS manufacturing system in the initial period. The lighter squares indicate the rework.

The similarity between the process-diagrams has caused the flow character of the production structure. Parallel shops were chosen for reasons of cost. Capacity utilisation is highest if all products can be produced on all processors. The consequences for the control systems will be treated in the following Section. As a result of the high capacity utilisation, lead times were long, and delivery times, therefore, were also long. They did, however, remain within customers' requirements in the first period.

Another consequence of a long lead time was a high rejection rate in inspection. Feedback on the substandard products was slow and, as a consequence, more faulty products were produced. Rejection rates were approximately 18 % in the first period. The customer constraints were not violated, because inspection took care of the rejection of faulty products. Costs incurred in production, however, were high.

Next, the design of essential and extra processors will be treated. In the second design phase of the manufacturing system design process, the processes are concretised.

Attributes become more concrete. Relevant attributes in this design phase are the time-related attributes. The capacity of different processors as well as set-up times and maintenance times are designed. The processors have been designed by choosing means. Decisions, therefore, have been taken on a more concrete level.

One of the processes concretised in this design phase is the deflashing process. After the SAS has been moulded and vulcanised, a flash remains. This flash is removed in the deflashing process, which in the first period was carried out by home-workers. Home-workers also visually inspected the products. The SAS, therefore, left PL twice. This resulted in long lead times for this processor, because SAS's were first collected in large batches, then transferred to the home-workers, and finally, after a relatively long processing time, transferred back to PL. The consequences for the control system will be treated in the next Section.

Extra processes and processors have been introduced. Buffer-, and inspection-processors have been added to the production structure. Buffers were necessary for the decoupling of the different departments. Inspection processors were necessary to guarantee the quality demanded. An additional sample inspection processor was necessary to check the home-workers' inspection. These were already incorporated into the production structure in Figures 6.11 and 6.12. The resulting processor-diagram is similar to the production structure visualised in Figure 6.11 with the addition of buffer-processors between all processors. The processor-diagram can be used as a starting-point for the final phase in the manufacturing system design process. This design phase will be treated in the next paragraph.

Means

The third and final phase in the manufacturing system design process involves the design of the means. Extra transport-processors have been added to the processor-diagram. The concrete elements and their structure are determined in this phase. A list of all means will not be given, since this information would not improve insight into the PL manufacturing system design process.

The structure of the elements designed in this design phase is visualised in a floor-plan. Figure 6.13 shows the floor-plan that existed in the first period. Similar means are arranged together. This type of floor-plan is called process-oriented. Since, however, the production structure is a flow of parallel shops, the floor-plan, on a different level of modelling abstraction, can be seen as product-oriented. Similar means are arranged together, because, by doing so, process knowledge can easily be exchanged and dirty and noisy means will not disturb personnel in other departments. The resulting floor-plan performs well with regard to the flow of material. Communication, however, between different departments is sub-optimal, because of their physical arrangement.

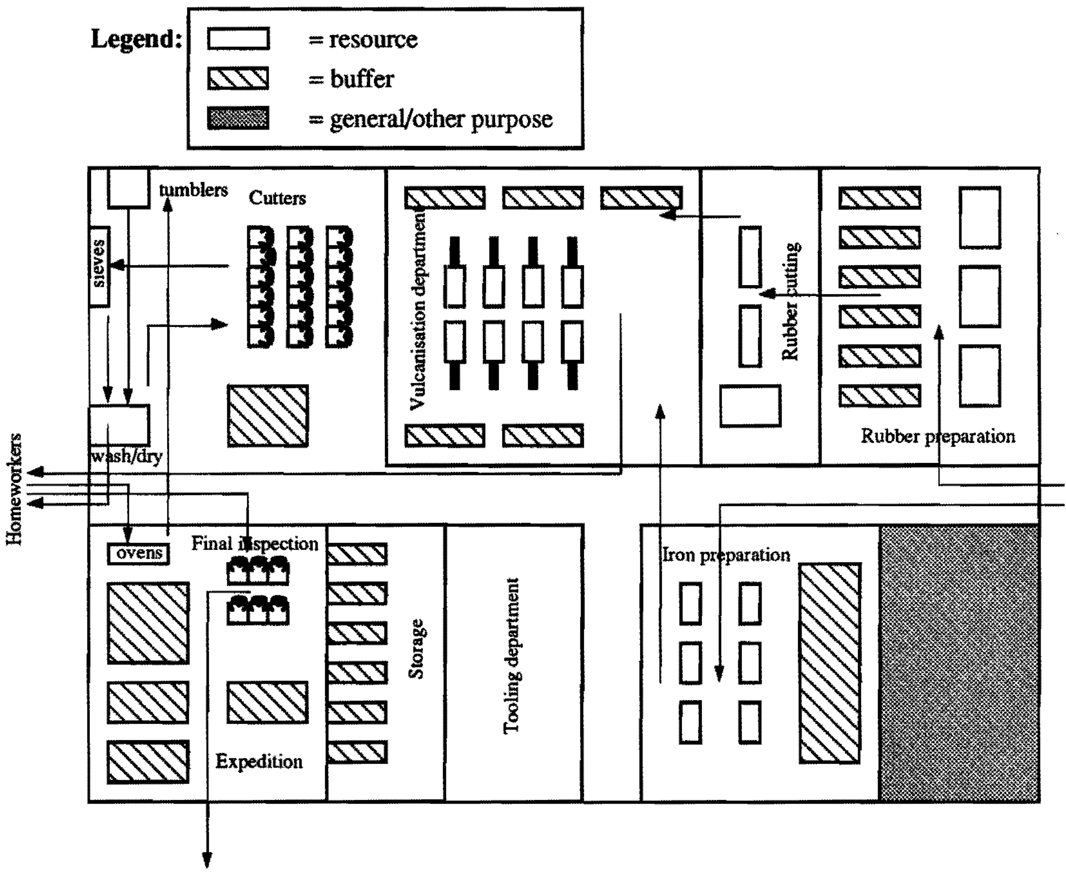


Figure 6.13. The floor-plan in the initial period.

The selection of the means has taken place after the processes were selected. Selection criteria were cost and quality. No explicit attention has been given to the structure of the means. Their physical arrangement automatically implied a production structure. The second design phase, therefore, has received little real attention.

The manufacturing system design process has been discussed in this Section. The next design step in structured design involves the design of the control system. The design of the control system will be treated for the first period in the next Section.

6.2.4. PL Control System Design in the First Period

After the design of the manufacturing system, the control system is designed in structured design, proposed in Chapter 4. The design of the control system will be treated in this Section. The consequences of choices made in the manufacturing system design process for the control system design process will be treated.

Figure 4.23 shows that the design of the control system can be started in parallel to the design of the manufacturing system processors. The control system has a strong relation with the production structure. The choices made concerning the production structure, therefore, strongly influence the quality of the control system. The production structure has been classified as a flow of parallel shops with little back-flow. The control of this structure will be relatively complex, because all products can be processed by all processors. Since production capacity is chosen such that a high capacity utilisation will result, scheduling will be essential, but difficult. Lead and delivery times will consequently be long.

The home-workers were another complicating factor in the manufacturing system. The material flow was disturbed, because products left the factory twice. Lead and delivery times were even longer. Error traceability decreased further. The control system, therefore, was relatively complex in the first period. A total of five system-hierarchical levels was necessary to control the PL manufacturing system. Large amounts of data were needed to control and trace products. Overhead costs, therefore, were relatively high in the first period.

The design of the control system has briefly been discussed in this Section. The discussion revealed that decisions made in the manufacturing system design process strongly influenced the control system design process. A more structured approach to the design process would have exposed these consequences.

6.2.5. Conclusion

The first period in the PL history has been discussed in Section 6.2. It showed that objective attributes were stable and not particularly strict. The product design process is almost entirely part of the objective definition phase. PL product designers only make design decisions on a low level of design abstraction. The manufacturing system design process has been traced using the three phases that have been proposed in Chapter 4. This showed that little explicit attention was paid to the second design phase in which the manufacturing system structure is determined. Indeed most design decisions were taken on a low level of design abstraction. This resulted in long delivery times and low quality. The low quality was corrected by the introduction of extra inspection processes, whereas the long lead times were actually within customer requirements. Because of the implicit choices made for the production structure, the control system was relatively complex and expensive.

The first period has been discussed above. Towards the end of the first period, objective attributes changed. Different weighing, therefore, was required, in turn necessitating substantial changes in the industrial system. This will be discussed in the next Section.

6.3. The Second Period: the Reorganisation

After a long period of stable product and production system design, the environment of PL began to change. Developments in the automotive industry resulted in a tendency towards shorter delivery times, higher quality and lower cost. Substantial changes were necessary in the PL industrial system in order to remain competitive. The changes made during the reorganisation in the early nineties will be traced using structured design. Firstly, the definition of the objective will be treated.

6.3.1. PL Objective Definition in the Second Period

The first step in structured design involves the definition of the objective. A three-step procedure for objective definition has been proposed in Section 4.1. The first two steps involve the identification of the Interested External Systems (IES's) and of the relevant attributes on which the IES's place constraints. These two steps have been described in Section 6.2.1 for the PL industrial system. The differences between the relevant attributes in the first and second period will be treated here. The attributes will be discussed for each IES. After this, the third step in the objective definition procedure, the weighing of attributes, will be treated.

Suppliers

Firstly, the relevant attributes for the suppliers will be discussed. Towards the end of the first period, developments in the automotive industry forced suppliers to decrease prices and delivery times and, at the same time, increase quality. Suppliers' suppliers were also forced to follow this trend. This made it possible for PL to deal with more demanding customer requirements. Changing customer requirements will be treated in the next Section.

Customers

Customer requirements changed towards the end of the first period. Table 6.1 shows the relevant attributes constrained by the customers. These will be treated consecutively, starting with the functionality and quality. Customer requirements on functionality have remained unchanged. Customer requirements on quality, however, have increased. The application of oil with better environmental attributes, for instance, implies a more aggressive environment for the SAS. In addition, a guaranteed life-span of three years was demanded.

The attribute price was also subject to change. Roughly, prices followed inflation levels, whereas the increased quality requirements demanded ever-increasing amounts of work. The price per unit work, therefore, decreased.

Thirdly, the attribute delivery time will be treated. PL's customers strove for a 'Just-in-Time' variant of production. This implies that stock is kept as low as possible and that everything should be supplied at the moment it is needed. This simple concept has strong implications for suppliers. Maximum delivery times, therefore, decreased from 12 to 2 weeks.

Two aspects of the attribute amount will be discussed. The amount of products produced in the late eighties and the early nineties is shown in Figure 6.5. A gradual increase of more than 10 % per year can be observed. Besides this, the amount of product types also changed. Figure 6.3 clearly shows the explosion in the amount of product types. Figure 6.4 shows a cumulative Product-Quantity diagram, showing the relation between the product types and the number of products demanded. The form of this graph was identical in all periods.

Financiers

After the discussion on the changes in customer behaviour in the second period, the financiers' requirements will be treated. These requirements are taken to be constant. The attribute ROI, therefore, remains 12 %. Next, changes in the labour market will be treated.

Labour Market

Two attributes were identified for the labour market. The attribute salary roughly followed inflation levels. Requirements of the attribute job satisfaction, however, changed more substantially. Noise, dirt and heat, especially in the vulcanisation department, became unacceptable.

Above, changes in all four relevant IES's have been discussed. Next, the weighing of the relevant attributes will be discussed.

Weighing of the Attributes

The third step in the objective definition procedure involves the weighing of the different attributes. Towards the end of the first period, changes in the environment forced PL to weigh the attributes differently. Customer priorities changed from price to quality and delivery time. Requirements in the labour market also caused differences in weighing.

Table 6.3 shows the weighing of the attributes in the second period [Boshuisen, 1993]. The higher an objective attribute is represented in Table 6.3, the more important it was judged by PL management. Comparison of Table 6.2 and Table 6.3 shows the growth of significance of especially the customers objective attribute delivery time. Personnel objective attributes also have grown in significance.

Table 6.3. Weighing of the objective attributes.

Customers functionality (quality) delivery time price
Personnel salary working conditions
Financiers Return on Investment
Suppliers all objective attributes

The different values of the attributes and the different weighing made redesign of the PL industrial system necessary. The redesign process will be discussed using structured design in the following Sections. Product design will, therefore, be treated first.

6.3.2. PL Product Design in the Second Period

After the definition of the objective, product design is the first step in the industrial system design process. The product design process will be discussed in the context of structured design. As in the first period, most of SAS design is part of the objective definition. Customers, in other words, determine most of the product design. The influence of PL product designers on the product design process, therefore, is limited to the concrete phases of the design process.

Paragraph 6.3.1 discussed the definition of the objective in the second period. There, changing requirements on product design have been signalled. Higher quality and more product types were signalled as predominant aspects. This implies greater involvement of PL product designers. More communication between PL product designers and customers' designers became necessary. Developments in the automotive industry show a tendency towards closer supplier-customer relations. Product design plays a central role in this.

The changing customer requirements have been discussed quantitatively in Section 6.3.1. The next basic sub-system that is designed in structured design is the manufacturing system. The design of the PL manufacturing system will be treated for the second period.

6.3.3. PL Manufacturing System Design in the Second Period

The objective definition and the product design process have been discussed in the preceding Sections. The manufacturing system design process will be discussed next. The changes in the environment, expressed in the objective definition, and the product design made the redesign of the production system necessary. The design of the manufacturing system, the first basic sub-system of the production system, is treated in this Section using structured design.

Processes

The first phase in the manufacturing system design process involves the design of the manufacturing processes. The Section on processes in Section 6.2.3 discussed the selection of processes in the first period. Three processes can be selected: transfer, compression and injection moulding. Injection moulding was rejected for reasons of quality and consistency. This drawback still existed in the second period. Therefore, transfer and compression moulding remain. Compression moulding has been selected for the same reasons as in the first period.

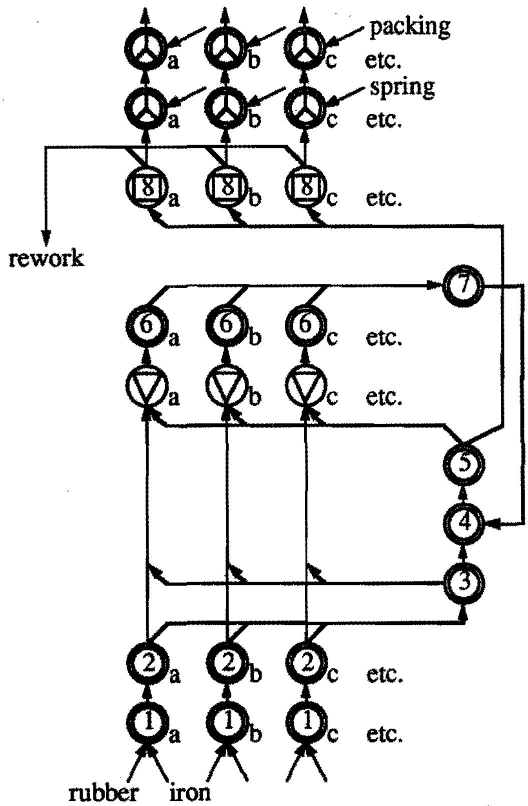
Process selection in the second period is identical to process selection in the first period. Process diagrams, therefore, are identical to the process diagrams presented in Figures 6.7 to 6.10.

Processors

The design of the processes in the second period has been discussed in the previous Section. No substantial changes were made in the process-diagrams. The second phase in the manufacturing system design process involves the concretisation of the processes. The processors are designed in this design phase. The changes in the environment and product design have influenced decision-making in this phase of the design process. Redesign of the manufacturing system was constrained by the restriction that no new means (and, consequently, processors) should be introduced. Therefore, only the structure of the processors could be changed.

Changes in the environment made shorter lead times necessary. Figure 6.11 and 6.12 showed that the structure in the first period can be seen as a flow of parallel shops. The parallel shops introduce extra controlling effort and longer lead times. In addition, rejection rates in the first period were high, because feedback of information was slow. This effect can be mitigated by shorter lead times, since early detection is improved by quick feedback.

The shorter lead time can be realised by changing the structure of the manufacturing system. If products are allocated to specific machines, production groups can result. These production groups exhibit a line structure. Figure 6.14 shows the production structure in the second period. Figure 6.15 shows the incidence matrix representation of the production structure. The production structure represented in these figures can be classified as a collection of flow shops. Extra processes (processors) are added to the production structure to make the processor diagram. The extra inspection processor is no longer necessary, because all inspection is done by PL personnel. This results in the processor-diagram, being the production structure with extra buffer processors added.



1 = compression moulding press
2 = deflasher
3 = additional vulcanisation ovens (4)
4 = tumblers (3)
5 = washing/drying machines (2)
6 = cutter
7 = sieves (2)
8 = visual inspector

Figure 6.14. The production structure in the second period.

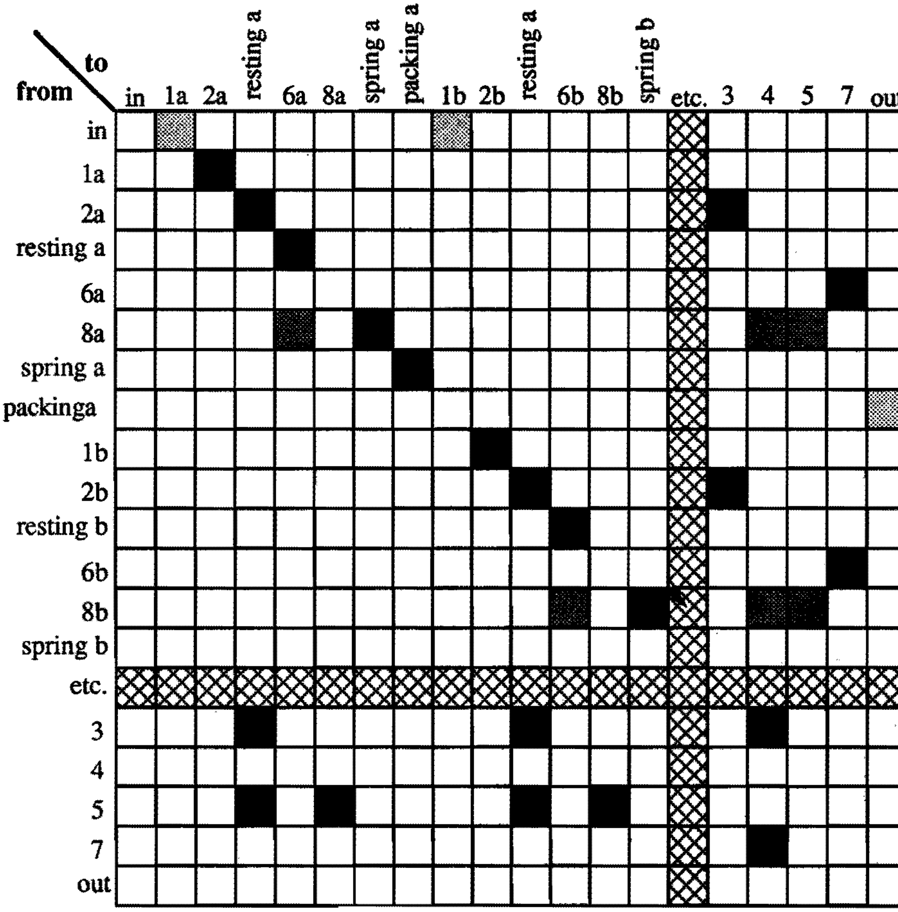


Figure 6.15. The production structure in the second period using the incidence matrix. Note that the representation is on the level of single means, in contrast to the representation in Figure 6.12, where the representation used parallel shops, being groups of means.

Figures 6.14 and 6.15 show that the production structure in the second period improved the performance of the manufacturing system in different areas. Production lines are formed, each producing a dedicated set of products. Lead and, consequently, delivery times were lower. This also enabled quicker feedback on deficiencies and, therefore, higher quality and lower rejection rates. The latter will be discussed in the next Section on the design of means.

Lead times in the second period were 2 weeks. This represents a reduction by a factor of six in comparison to the first period. Alongside this apparent advantage, some disadvantages to this structure should be mentioned. Since products are allocated to a sub-set of all possible processors, volume flexibility is low. If ordering frequencies and amounts are fluctuating, a more flexible production structure is required. This disadvantage has not been recognised in the design of the structure of the manufacturing system. A more structured approach would possibly have better evaluated advantages and disadvantages.

The redesign of the production structure and the processor-diagram has been discussed in this Section. Other relevant design decisions concerning the manufacturing system have been taken on the most concrete design phase in which the means are designed. This will be discussed in the next Section. After that, the consequence of a different production structure for the control system will be treated in the Section 6.3.4.

Means

The third and final phase in the manufacturing system design process involves the design of the means. The processors, designed in the previous phase, are concretised in this phase. Two aspects of decision-making in this design phase will be treated. Firstly, the design of the means, and secondly, the structure of the elements will be discussed. This is expressed by the physical arrangement of the means.

The basic assumption in the redesign process was that no new means should be introduced into the manufacturing system. Investments, therefore, could be kept low. Exceptions to this rule are the home-workers. Deflashing and inspection were performed by home-workers in the first period. Lead times, however, were long. Therefore, deflashing and inspecting in the second period were performed by PL personnel. Salary costs were higher, but it was expected that the gain in lead time would compensate for this.

Secondly, the physical arrangement of the means will be treated. Products have been allocated to processors in the previous design phase, and the most relevant means in these production cells grouped together. One vulcanisation press was grouped with a cutter, a spring assembler, an inspector and a packer. Figure 6.16 shows the resulting floor-diagram.

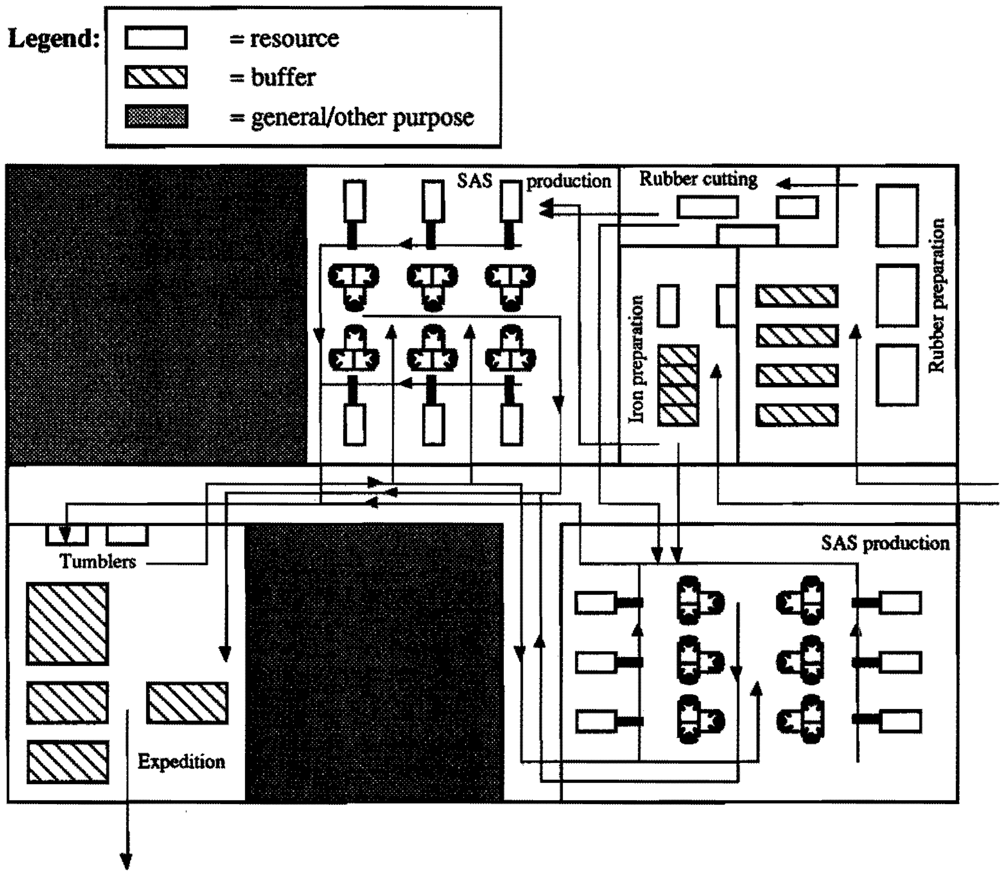


Figure 6.16. The floor-plan after the redesign.

It can be seen in Figure 6.16 that material flow often leaves the production cells. Material flow, therefore, was sub-optimal in the second period. The reason for this was that the production structure has not been used as a starting-point for the design of the physical arrangement. Communication, however, between the most relevant means was improved. Feedback on defects was quicker. As a consequence, rejection rates were 8 % in the second period. Compared to the first period, this is an improvement by more than a factor of two.

Conclusion

The redesign of the manufacturing system has been discussed in this Section. No changes were made in the most abstract design phase. Process-diagrams in the second period were identical to the process-diagrams in the first period. Substantial design decisions have been made in the second phase, in which a new production structure has been designed. Design decisions have also been taken in the third design phase. All deflashing and inspection is done by PL personnel, resulting in higher direct cost, but improved quality and delivery time. The physical arrangement of the means is optimised with respect to the communication between the most relevant production processes (means). Material flow, however, is sub-optimal.

Another objective attribute that is affected by the physical arrangement, is the job satisfaction of the personnel. Operators working in the vulcanisation department in the first period worked in a noisy, dirty and hot environment. This is improved by the new arrangement of the means, because presses are placed on larger surfaces and better exhaust hoods have been installed.

The next basic sub-system that is designed in structured design is the control system. The redesign of the control system will be treated in the next Section.

6.3.4 PL Control System Design in the Second Period

After the design of the manufacturing system, the control system is designed. The consequence of decisions taken in the manufacturing system design process will be briefly discussed in this Section.

The main disadvantages of the manufacturing system in the fist period were the complexity of the production structure and the use of home-workers. Long lead times resulted and quality was low, because of slow feedback. The control system was necessarily complex. Much data had to be stored and processed to control the manufacturing system. Error traceability was low. These disadvantages were eliminated in the redesign of the manufacturing system. The control system, therefore, could be simple. The small production lines were easy to control. The number of hierarchical levels in the PL control system decreased from five in the initial period to two in the second period, which resulted in a 20 % decrease of overhead costs.

This completes the treatment of the redesign of the PL industrial system. Changes in the environment of PL forced the reconsideration of design decision in product, manufacturing system and control system design. The consequences of the decisions made in the redesign project are summarised in the next Section.

6.3.5. Conclusion

The different constraints posed by the various IES's made redesign necessary. PL product designers became more involved in the product design process. More communication with customer designers was necessary. This followed the trend in the automotive industry of closer supplier-customer relations.

Most redesign decisions have been taken in the manufacturing system. A different production structure made possible a reduction in lead times from 12 weeks in the first period to 2 weeks in the second. The constraint placed on the objective attribute delivery time could now be met. The disadvantage of the newly designed production structure was its rigidity.

Changes in the physical arrangement of the means also had their implications. Quality figures improved, because quick feedback became possible. Cost was reduced, because less faulty products were made. Material flow, however, was sub-optimal. Besides this, job satisfaction changed. Personnel working in the vulcanisation department in the first period, now had a working situation in which heat, noise and dirt conditions were improved.

The control system has been simplified. This resulted in a sharp decrease of overhead cost. The net result of the redesign, therefore, was positive. The rigidity of the production structure and the sub-optimal material flow can be pointed out as the main negative aspects. It will be shown in the next Sections that this caused iterations on the redesign.

6.4. The Third Period: the Current Situation

The redesign of the PL industrial system has been discussed in the previous Sections. The changing environment made the adaptation of product, manufacturing system and control system design necessary. Currently, the PL industrial system works in yet another way. The reason for this is that it did not perform optimally. Customer requirements could not be satisfied. Design decisions that have been taken in the various basic sub-systems will be treated in the following Sections.

6.4.1. PL Objective Definition in the Third Period

The first step in structured design involves the definition of the objective. Figure 6.3 and 6.5 showed that towards the end of the first period the environment of the PL industrial system changed. This lasted until the current situation. Objective definition in the third period, therefore, is identical to the objective definition in the second period. Constraints placed on the industrial system, discussed in Section 6.3.1, are even more severe than in the second period.

Objective definition did not change substantially between the second and the third periods. The second step in structured design involves the design of products. This will be treated in the next Section.

6.4.2. PL Product Design in the Third Period

After the discussion on the definition of the objective, product design in the third period will be treated. It has been shown that most of product design is part of the objective definition. The situation in product design during the third period is identical to the situation during the second period. Constraints posed by PL's customers, however, have become even more severe. Consequently, PL product designers communicate even more with the designers of the customers.

No significant changes have been made in product design. The third step in structured design involves the design of the manufacturing system. This will be treated in the next Section.

6.4.3. PL Manufacturing System Design in the Third Period

Neither the definition of the objective nor product design had changed substantially. Nevertheless, the industrial system did not perform in an optimal way. The products, demanded by the customers, could not be supplied in the desired variety and quantity. Design decisions, therefore, had to be reconsidered. This will be discussed using the three phases in the manufacturing system design process.

Processes

The first phase in the manufacturing system design process involves the design of the processes. The processes that had been selected in the first period, have been sufficient in the second period. No alternative processes have been introduced, since injection moulding still is unreliable. Currently, PL is experimenting with the application of injection moulding of SAS's. This will be dealt with in the Section 6.5.4.

Process-diagrams in the third period, therefore, are identical to the process-diagrams in the first and second period. Design decisions concerning the second design phase have been reconsidered. These will be discussed in the next Section.

Processors

The second phase in the manufacturing system design process involves the design of the processors. Two aspects of processors design will be discussed: the design of the elements, and the design of the structure.

The processors in the third phase are the same as those in the second period. The reason for this is the basic assumption that the same means should be used. As a consequence, capital outlay for the redesign will be minimal. Only the structure of the processors, therefore, can be redesigned.

The structure that existed in the second period was easy to control and resulted in short delivery times and higher quality. The disadvantage of this structure was its rigidity. The diversity of the products and the fluctuations in demand were the cause of this structure proving to be less suitable in the PL situation. The cumulative Product-Quantity diagram in

Figure 6.4 had already shown that a volume-flexible structure was required. Developments in the automotive industry too had placed increasing demands on product diversity and volume flexibility.

The structure, therefore, needed to be reconsidered. This reconsideration was in fact done by changing the control system. All means in the manufacturing system remained the same. Even their physical arrangement did not substantially change. The change in the control system, however, caused a change in the production structure.

The production structure that currently exists resembles the structure in the first period. The difference is caused by the home-workers in the initial period. Extra sample inspection processors were required to check the home-workers' inspection. Figure 6.11 and 6.12 show this structure. It can be classified as a flow of parallel shops. The control of this structure is more complex and lead times will be higher. It is, however, better able to cope with fluctuating requirements. The redesign of the production structure will be discussed in the Section on the control system design, where, it will be shown that decisions concerning the control system also changed the production structure.

The changes in the production structure have consequences for the design of the means. This will be discussed in the following Section.

Means

The final phase in the manufacturing system design process involves the design of the means. It has already been stated that no substantial changes have been made to the physical arrangement of the means. The control system has been changed. As a result of the strong relations between the structure of the manufacturing system and the control system, the production structure also changed. This, in turn, had consequences for the means.

The floor-plan in the current situation is the same as the physical arrangement in the second period, and is illustrated in Figure 6.16. The advantage of fast feedback, therefore remains, because inspectors are close to the operators of other important processes. Material flow, however, is sub-optimal. The physical arrangement is based on the formation of groups, although current production can be seen as a flow of parallel shops, see Figures 6.11 and 6.12.

Changes in the control system have caused changes in the manufacturing system. As a result, the PL industrial system performs within the constraints of its environment. The redesign of the control system will be treated in the next Section.

6.4.4. PL Control System Design in the Third Period

The control system is designed after the design of the manufacturing system in structured design. The relations between the control system and the manufacturing system implied that redesign of the control system had strong implications for the manufacturing system. The redesign of the control system will be discussed next.

The PL industrial system did not perform within constraints posed by its environment. The production system was not capable of producing the diversity of products in the desired amounts. Main reason for this was that products assigned to one group could not be produced on other means. The fluctuations in the product requirements were such that this rigidity caused problems. Controllers in the control system, observing this phenomenon, were left with only one course of action. The rigid production structure was unworkable. Controllers, therefore, had to assign products to other means, thus implicitly changing the production structure into a more flexible one.

Now, the PL industrial system performs within the constraints posed by its environment. This is due to the flexibility and quality of the controllers in the control system. The design of the manufacturing system, however, is still based on a different concept. The PL industrial system can still be improved. This will be treated in the Sections on the future situation.

6.4.5. Conclusion

The PL industrial system design process has been traced using structured design, discussed in Chapter 4. After a long stable situation, the environment began to change. PL was forced to redesign. Firstly, substantial changes were made to the structure of the manufacturing system. As a result, the physical arrangement of means could be optimised and the control system could be greatly simplified. Nevertheless, the industrial system did not yet perform optimally. Due finally to the flexibility and quality of the controllers the system does now perform within constraints.

The structured design method discussed in this dissertation has not been used in the redesign project. The use of structured design would possibly have avoided the iteration that was necessary in the third period, because the consequences of choices would have been recognised in an earlier phase. Design in the concrete phase in the manufacturing system design process would have been optimised using the production structure and the processor-diagram as a starting-point. Also, a different floor-plan would have resulted.

Although the PL industrial system performs within constraints, further optimisation still seems to be possible. The design of the PL industrial system will be discussed in the following Section.

6.5. The Fourth Period: the Future Situation

The changing environment required adaptation of the PL industrial system. The redesign of the basic sub-systems, discussed in the previous Sections, took place in two stages. The first stage did not satisfy the changing constraints posed by the environment, and an iteration was necessary. Relations were not considered sufficiently in the redesign project. A more structured approach would possibly have revealed the consequences of design decisions of the various basic sub-systems on the different levels of design abstraction. The previous Sections showed that the industrial system design method, described in Chapter 4, would have helped in considering these relations.

Future developments will be discussed using structured design. The various steps will be discussed consecutively. Firstly, future developments in the definition of the objective will be discussed.

6.5.1. PL Objective Definition in the Future

The first step in the design of an industrial system involves the definition of the objective. Three steps can be distinguished in the definition of the objective: the identification of Interested External Systems (IES's), the identification of relevant attributes upon which the IES's place constraints, and finally, the weighing of attributes. The first two steps have been described in Section 6.2.1.

Table 6.1 shows the relevant attributes. The discussion in 6.3.1 illustrated that requirements on PL have become more strict. This is caused by the developments in the automotive industry. The tendency to decrease delivery times and prices, whilst increasing quality has triggered similar developments in the suppliers. Growing competition and saturation of the automotive market will make constraints even more severe. Customer requirements, therefore, will remain most important. Growing prosperity and welfare will also change constraints posed by the labour market. Both salary and job satisfaction requirements will become more demanding.

Constraints placed on the PL industrial will change further. Requirements on the system will increase. The weighing of the IES's and their relevant attributes, however, will be the same as the weighing in the second and third period. The influence of the changing environment on product and production system design will be discussed in the next Sections, starting with product design.

6.5.2. PL Product Design in the Future

The changing environment, expressed in the objective definition, will influence the design of products. Functionality requirements will be stable. Quality requirements, however, will increase. As a consequence, the product design process will become more laborious. Relations between suppliers and customers will grow even closer. PL product designers, therefore, will communicate with the designers of the customers to further improve SAS design.

Most of the product design process will remain part of the objective definition. The functionality and structure of the SAS's will be stable. The influence of PL product designers will be limited to the concrete phases of the design process. There, standardisation of the product design will possibly have a positive influence on the cost and quality of the product object designs. The product design process may also evolve more quickly. Paragraph 6.3 showed that the increase of the number of product types had negative effects on the production system. Standardisation of product object designs, therefore, may have positive effects on the production system. These positive effects have been discussed in Chapter 4.

The influence of the changing environment on future product design has been discussed in this Section. Next, the design of the manufacturing system will be treated.

6.5.3. PL Manufacturing System Design in the Future

After the definition of the objective and the design of the products, the manufacturing system can be designed. Again, the manufacturing system design process will be discussed using the three phases that have been introduced in Chapter 4, beginning with the design of the processes.

Processes

The first phase in the manufacturing system design process involves the design of the processes. The design of the processes in the PL manufacturing system has been treated in previous Sections for different time periods. There, it was seen that most processes have been selected for reasons of availability and cost. The cheapest process, capable of processing the material in a desired way was selected.

The most relevant process in the PL manufacturing system is the process in which the rubber is formed and vulcanised. Basically, three processes are capable of processing the rubber: transfer, compression and injection moulding. In the first, second and third period, injection moulding did not produce satisfying results. Quality and reliability were too low. Transfer and compression moulding, therefore, remained as eligible processes. Currently, PL is studying the use of injection moulding as an alternative for transfer and compression moulding.

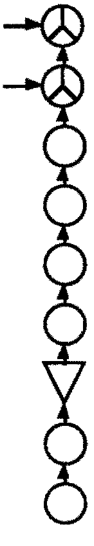


Figure 6.17. Part of the process-diagram with the application of injection moulding.

The use of injection moulding will have great influence on the production system. Since injection moulding can be a flashless process, the deflashing process can be eliminated. The home-workers, the human means performing the deflashing process, caused lead time problems in the past. These problems will no longer exist should injection moulding produce flashless semi-manufactures. Figure 6.17 shows the finishing part of the process-diagram of a general SAS were injection moulding to be applied.

The process-diagrams of all product types will be used as a starting-point for the second design phase. The design of the processors will be treated in the next Section.

Processors

The second phase in the manufacturing system design process involves the design of the processors. Two aspects are designed in this design phase: the elements and their structure. The redesign projects in the past were constrained by the fact that no extra means were to be introduced in the manufacturing system. The processors, therefore, were also known. As a consequence, only the structure of the processors could be altered.

It has been shown that the structure of the manufacturing system has a strong relationship with other design decisions. The design of the structure, therefore, determines the performance of the industrial system. A systematic redesign of the production structure and the processor-diagram, based on the process-diagrams, can optimise current production structure. Redesign should pay attention to relevant attributes and other basic sub-systems. The structure of this design problem, treated in Section 4.4.2, can be used in the redesign of the structure of the manufacturing system.

The application of injection moulding also has strong implications for the design of the processor structure. Figure 6.18 shows a possible production structure that could follow from the process-diagram in Figure 6.17. The elimination of deflashing, and, consequently, extra tumbling, washing and drying, simplifies the structure. It can be seen in Figure 6.17 that the only back-flow is caused by rework. The rest of the structure can be classified as a flow.

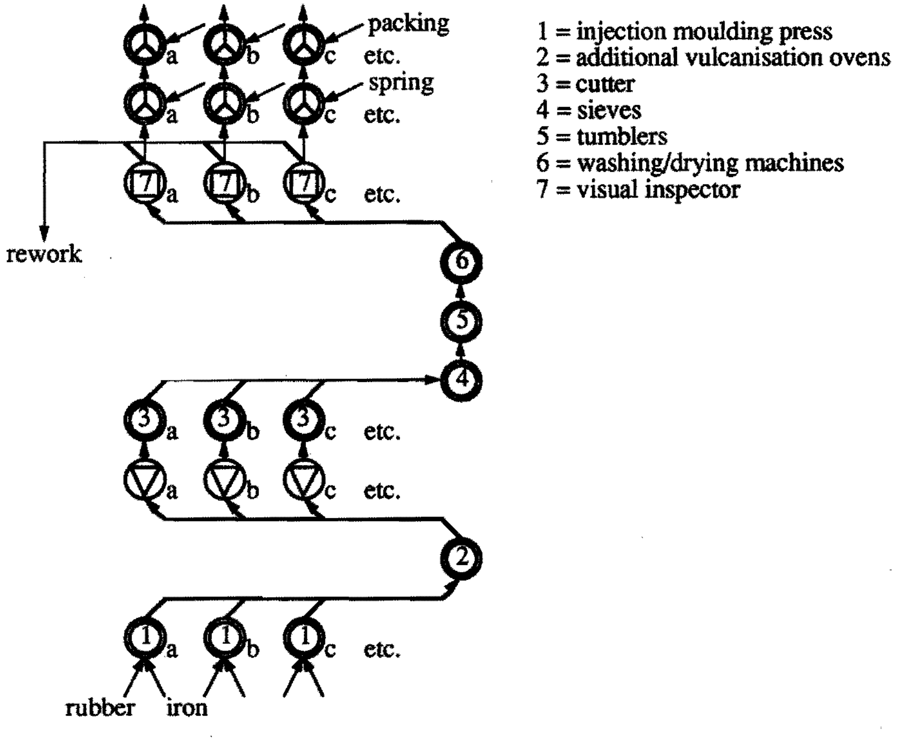


Figure 6.18. The processor-diagram of PL with the application of injection moulding.

After the design of the processors of the manufacturing system, the processors are concretised. The manufacturing system design process is finished in the third phase, in which the means are designed. This will be treated in the next Section.

Means

The second phase in the manufacturing system design process is completed with a processor-diagram. This processor-diagram is a starting point for the design of the means. Both the elements and the structure of the elements are designed. The structure of the elements is represented in a floor-plan. It has been shown that the floor-plan in the current situation did not use the material flow as a starting point. Optimally, the design of the floor-plan will pay attention to all relevant attributes. Optimal communication, optimal material flow and optimal working conditions should all be taken into account.

As well as the floor-plan, the means will be designed. The application of injection moulding will cause more dramatic changes in the design of the means. Deflashing is no longer necessary. The structure of the manufacturing system will be simplified. As a consequence, different means will be selected and the floor-plan design will be different.

In this Section, the design of the manufacturing system for the future situation has been discussed. The design of the control system is treated in the next Section.

6.5.4. PL Control System Design in the Future

The final basic sub-system that will be treated for the future situation is the control system. Control system design has been discussed for different time periods in previous Sections. Initially, the control system was relatively complex. The growing diversity of the products made the control system more and more complex. Towards the end of the first period, changes in the environment of the PL industrial system were such that adaptation of product and production system were necessary. The first redesign yielded a production structure for which a much simpler control system could be designed. This industrial system, however, could not perform within the constraints posed by the environment. Adaptation of the control system made production within constraints possible. The control system, however, became more complex.

The systematic redesign of the PL industrial system will optimise both product and manufacturing system design. As a consequence, the control system will also change. The relation between the structure of the manufacturing system and the control system demands special attention in this redesign. A simple and efficient control system will then be able to control the manufacturing system within the strict constraints laid down in the future.

6.5.5. Conclusion

Future developments in the design of the PL industrial system have been discussed in the previous Sections. The constraints posed by the environment will become even more severe. Systematic redesign of the PL industrial system will yield a system that is able to perform within the constraints.

After the discussion of the different time periods in the history of PL, the PL industrial system design process will be reviewed. Conclusions concerning the structured and intuitive design of industrial systems will be drawn.

6.6. Conclusion

The structured design of industrial systems was discussed in Chapter 4, and a method for the structured design of industrial was proposed. This method has been used in this Chapter to trace the decision making process in different time periods in the history of an industrial system. By doing so, intuitive decision making has been compared with structured design.

It was seen that the changing environment had a strong influence on the performance of the industrial system studied in this Chapter, and necessitated a major redesign in the early nineties. The structure of the manufacturing system was the primary focus of interest in this redesign project. The discussion on the relation between the structure of the manufacturing system and the control system showed that the premise stating a strong relationship was correct. Not considering the disadvantages of the newly designed structure, however, has necessitated an iterative redesign. Structured design would have forced decision makers to describe objective attributes. The processor-diagram would have been designed using the problem structure described in Section 4.4.2. This processor-diagram would have been evaluated using these objective attributes, possibly revealing the shortcomings, that now have shown up in use, before implementation.

The iteration of the redesign project was successful due to the quality and flexibility of the controllers in the control system. This, however, caused a change in the structure of the manufacturing system. As a consequence, the current manufacturing system seems to be sub-optimal. The means design is based on the previous processors design, whereas the current processors design is based on the relation with the renewed control system. Another iteration on the means design would possibly improve this situation.

The redesign of the PL industrial system is restricted by the fact that most of product design is part of the objective definition. The rest of the design process, therefore, starts with the design of the manufacturing system. The redesign of the processes in the manufacturing system design should take into consideration the use of injection moulding as an alternative for compression moulding. Currently, PL manufacturing system developers are working on the application of injection moulding. The redesign of the processors and their structure could further improve the performance of the PL industrial system. The structure of this design problem discussed in Section 4.2.2 can be used as a starting-point.

The example presented in this Chapter has shown that the quality of a design process can benefit from the use of a structured design method. Intuitive decision making is controlled. Relevant design decisions are pointed out to the designer, so that expensive iteration can be avoided. Industrial systems will be designed more optimally and, consequently, industrial systems will be more competitive. The integration of the influence of a dynamic environment into structured design takes care of a dynamic instead of a static industrial system.

The structured design of industrial systems has been discussed in this dissertation. A summary of current design research was presented in Chapter 2. The structuring of design processes was treated in Chapter 3. The theory developed in this Chapter was used in Chapter 4 to structure the design process of industrial systems. An empirical test of structured design was presented in Chapter 5. Finally, an illustration of structured design was presented in this Chapter. The dissertation will be completed with a review in the next Chapter. Suggestions for future research are given in Chapter 8.

Chapter 7

Conclusion

The design of industrial systems has been discussed in this dissertation. Chapter 2 dealt with different areas in design research. It showed that modelling techniques for both products and production systems can be used throughout the design process. Design methods have been developed that support decision-making. Recently, more attention has been paid to the more abstract phases of the design process. As a result, modelling techniques that can be used in abstract phases and design methods that support abstract decision-making have become available. The deployment of both modelling and design techniques, however, is not done in a structured way. The attention of the designer is directed exclusively to the *object design*, while the *design process* is moved through in an intuitive way. Designing or structuring this design process is claimed to be a way to improve the results of the design process. The industrial system design process, in other words, would benefit from a structured approach. The three research objectives that have been stated for this research project were as follows: (1) the development of concepts for the designing (structuring) of design processes, (2) the development of a structured industrial system design method and (3) the prove of the claimed benefits of structured industrial system design.

The structuring of design processes has been treated in Chapter 3. It showed that three aspects are relevant in the structuring of design processes: the *sub-systems*, the *attributes* and the level of *design abstraction*. These three aspects can be represented in a *design cube*. Design can be seen as moving from the upper plane in the design cube to the lower plane. The structuring of the design process is equivalent to the division of this design cube, in other words the structuring of the way the designer moves through the design cube.

The three axes of the design cube have been discussed in turn. An object design can be modelled by a network of attributes. Filling in the network makes the object design more concrete. Two phases can be distinguished. Interested External Systems fill in the network in the objective definition phase. The designer fills in the network in the rest of the design process. The rest of the design process can also be divided into levels of design abstraction. There is, however, no fundamental reason to prefer a particular number of phases. Each situation can and should be structured individually. Dependent on the design problem and the individual designer an appropriate number of phases should be chosen. The introduction of phases into the design process has two main advantages. The designer is guided in his decision-making, such that important strategic design decisions are treated with special attention and, in addition to this, design documents result after each design phase. Communication and evaluation possibilities improve, because the conceptual model that existed in the designer's mind is made explicit.

The making of design decisions concerning an object design has been modelled as filling in a network of attributes. The human decision-making process has been modelled in many different ways. More cognitive research is necessary to formulate a detailed model of human decision-making. In this dissertation, human decision-making is modelled as a cycle of four steps: (1) analysis; (2) synthesis; (3) evaluation; (4) decision. Other researchers give similar decision cycles. Design, therefore, can be seen as the filling in of the network of attributes by the application of the decision cycle. The support of design decisions should, therefore, consist of methods and techniques for all 4 steps of the decision cycle.

Decomposition and composition of sub-systems have been defined. These concepts are related to the action of dividing a system into sub-systems and vice versa. Top-down and bottom-up design were discussed. Top-down design is an extreme form of design in which only decomposition is applied. Bottom-up design is another extreme form in which, firstly, the system is decomposed into elementary sub-systems and, secondly, the elementary sub-systems are composed into optimal sub-systems. Sequential and parallel design have been discussed. These concepts are related to the organisation of the design process. The consecutive design of sub-systems is called sequential design. The simultaneous design of sub-systems is called parallel design. The concepts of (de-)

composition, top-down, bottom-up, sequential and parallel design are all closely related and should not be confused.

A procedure for structuring design processes has been provided. The procedure consists of five steps. Each design process starts with the definition of the objective. After this, the system to be designed is divided into basic sub-systems. Phases are then introduced in the design processes of the basic sub-systems, and the relevant attributes are identified for every phase of every basic sub-system. Finally, design methods are selected or developed to support decision-making concerning the relevant attributes for all four steps of the decision cycle. Figure 7.1 illustrates the five steps in the structuring of design processes. With this procedure, the first research objective has been achieved.

Procedure for the structuring of design processes
1. Formalisation of objective definition
2. Identification of basic sub-systems
3. Phasing of the design processes of basic sub-systems
4. Determination of relevant attributes
5. Selection or development of methods and techniques for: - analysis - synthesis - evaluation - decision

Figure 7.1. A procedure for the structuring of design processes.

The theory on the structuring of design processes is used in Chapter 4. The five-step procedure is used to structure the industrial system design process. After the objective definition is formalised, the industrial system is divided into basic sub-systems. The industrial system is divided into the products and the production system. The production system is divided into a manufacturing system, an information system and a financial system. The information system consists of a matter control system and a financial control system. Phases have been introduced in the design processes of every basic sub-system. Each design process has been divided into three phases. Relevant attributes have been identified and design methods have been selected for the various design phases of the basic

sub-systems. Particular attention has been paid to the manufacturing system. The product and the control system have briefly been addressed.
The second research objective was the development of a structured design method for the design of industrial system. The five steps of the structuring method, defined in Chapter 3, have been executed for industrial systems. By doing so, the second research objective has been achieved. Figure 4.24 shows the structured industrial system design process. The theory on the structuring of design processes, that has been defined and discussed in Chapter 3, can be used to adapt this standard structure to the individual situation.

Structured design can now be applied in real and laboratory situations. The assumed benefits of structured design can thus be tested, and indeed this has been done empirically. The empirical test investigated the deployment of structured design compared to intuitive design. Two hypotheses were formulated: (1) the designers using structured design will produce better object designs and (2) the designers using structured design will address more abstract design problems. It showed that the quality of the design process was improved by the application of structured design. The designers who used structured design paid more attention to the more abstract, strategic design phases. The second hypothesis, therefore, was supported by the test data. The designers using structured design paid more attention to other sub-systems and considered more aspects in their design decisions. The quality of their design decisions, however, was not improved significantly. The first hypothesis, in other words, was not supported by the test data. Too many other variables are involved. A negative result of addressing more abstract design problems was that the designers using structured design needed more time.
More empirical research is necessary to test structured design in different circumstances. The next Chapter will discuss some suggestions for future research.

The application of the structured approach has advantages over the intuitive approach. The case in Chapter 6 has illustrated this. It showed that structured design can help to identify significant design problems, structure the making of design decisions and lessen iteration. The structure as proposed in Chapter 4 has been used in other cases as well. There, it proved to be useful in the structuring of decision-making. Relevant aspects were considered with the requisite attention and relations between basic sub-systems have been considered carefully.

It might be said that structured design as proposed in this dissertation is not different from the way that designers already perform, or that the structure limits the designers in their creativity. Structured design can be claimed to be a researcher's hobby, but of no practical significance. The empirical test, however, clearly showed the differences between structured design and the conventional approach. This, an experienced designer might say, bears no relation to actual design. The tendency, however, to focus on concrete design problems can also be observed in practice. The redesign projects that have been executed during this research project all had a problem formulation that focused on concrete design problems. The majority of industrial system redesign or reorganisation projects focus on aspects that can actually be observed and, therefore, on concrete design problems. Structured design can help to locate and solve the real design problem. Structured design has already proven to be a suitable instrument to this end.

More research, however, is required. Many different areas need closer investigation. The next and final Chapter will discuss the options for future research.

Chapter 8

Future Research

Structured design of industrial systems has been discussed in the previous Chapters. Many questions have been raised in this research. Some of these need closer examination. This Chapter will discuss some options for future research. Firstly, research concerning the modelling of design processes will be treated. Then, research on the modelling of object designs will be given attention. The development of design methods to be used in structured design will be examined. Finally, the structuring of other design processes will be dealt with.

Firstly, the modelling of design processes will be discussed. The modelling of design processes concerns the modelling of human decision-making. Design can already benefit from the results of this research. Techniques have been developed that facilitate the solution of problems that formerly were too complex. Rule-based systems and neural networks are examples of such techniques. Detailed models of the human decision-making process, however, are still far away. Design process models need empirical testing to prove their validity. Many global models of the design process are based on introspection and are not validated. The development of validated global and detailed design process models can help designers to further improve decision making.

The decision cycle has been used to model human decision making. More cognitive research is necessary to formulate detailed models of human thinking and decision making. This research can also reveal the way a designer moves from the upper plane in the design cube to the lower plane. The general statements that have been given in Chapter 3 of this dissertation on the structuring of design processes can then be formulated more precisely. The relation of the structuring of design processes with aspects like the quality, creativity, experience of the individual designer and with aspects like the complexity and degree of innovation of the design problem should be investigated.

With regard to the modelling of object designs, current techniques focus on the concrete phases of the design process. Besides this, only few attributes can be modelled. As a result, formal evaluation of these models can only be made concerning the attributes that have been modelled. Other relevant attributes need to be evaluated using mental simulation. The development, therefore, of formal modelling techniques that enable the modelling of many (relevant) attributes is required. These models can be formally evaluated concerning a set of relevant attributes. By doing so, sub-optimisation is prevented. Modelling and evaluation techniques need to be developed not only for concrete phases, but also for abstract phases.

Next, the filling in of the structure proposed in Chapter 4 will be discussed. A structure for industrial system design has been proposed in Chapter 4. This structure can be – and has been – used in design projects. It, however, needs to be substantiated with design methods. The four steps in the decision cycle need support. Methods and techniques should be developed for analysis, synthesis, evaluation and decision-making. Chapter 4 discussed the relevant attributes that should be considered. The development of design methods can use the structure of the design problems, defined in Chapter 4, as a starting-point.

Structured design can have the disadvantage that the design processes evolve slowly. The structure is developed such that an optimal result is achieved only when all phases of all basic sub-systems are addressed. This, however, is laborious. Instruments may be developed that help to identify the essential design problems. Part of the structured design is then used to guide the inventarisation of data; another part is used to guide decision making. The disadvantage of slower design processes can thus be eliminated.

The concepts that have been defined and discussed in Chapter 3 have been applied for industrial system design. This theory, however, can also be applied to other design processes. The design processes of, for instance, software and buildings can be structured using these concepts. Research, however, is required verify this. Currently, the theory is used to structure the design process of distribution systems [Van Bemmel, 1993; Van Bokhoven, 1993; Van der Burght, 1993; Rulkens, 1993; Van Der Wielen, 1993; Mikkers, 1994].

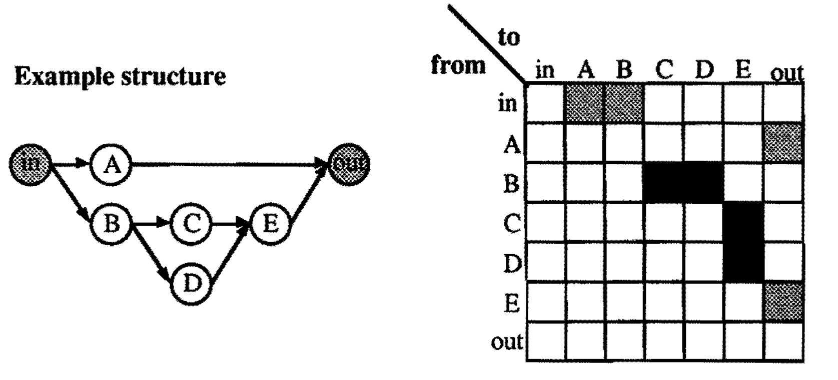
Formalising the industrial system design process was claimed to be impossible. The complexity of the matter could only be dealt with by experienced and skilled designers. The research presented in this dissertation has shown that structuring the design process can help to improve the quality of object designs. Whilst full formalisation of the industrial system design process might presently be impossible, improvement of the quality of the design process by the deployment of structured design has proved to be possible.

Appendix A. The Representation of Production Structures

Production structures and processor-diagrams can be visualised in different ways. One way is the draw all processor as icons and all material flow as arrows between the icons representing the processors. This drawing technique has the advantage of ease of communication and interpretation. It is visualised as it will be realised. Disadvantage, however, is the fact that the type of structure cannot easily be identified. Therefore, the incidence- or cross-matrix representation can be used.

In this appendix, some typical examples will be shown in the conventional and the incidence-matrix representation. Besides this, guidelines will be given for the analysis of the incidence-matrix.

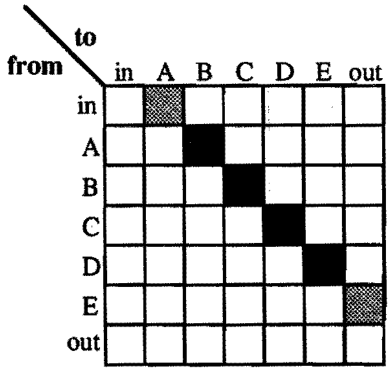
Representation



The presence of a material flow between processors X and Y is visualised by a ■ in the incidence or cross matrix.

Above, the representation of an example production structure is shown. A material flow relation is visualised with a black square. Quantitative information can also be used. The material flow between processor X and processor Y can, for instance be denoted in tons per day or pallets per week.
Below, some typical examples of production structures are shown.

Line structure

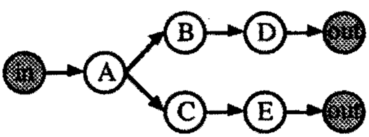


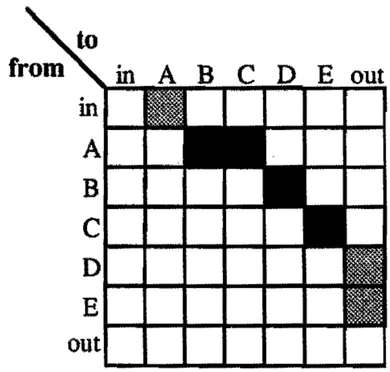
Example 1.

The line structure (or flow shop) is the most simple production structure. It can be identified in the incidence matrix representation by the sole presence of black squares just above the top-left to bottom-right (TLBR) diagonal.

The products are processed on N sequential processors. Control of this kind of structure is simple. Control can become somewhat more complex if products are allowed to pass each other in the line. Dispatching rules can for instance be used to control this passing of products.

Divergent structure



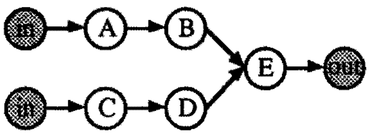


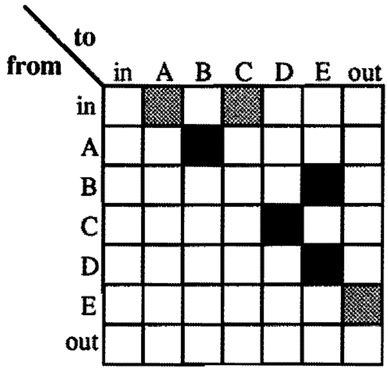
Example 2.

A divergent structure can be identified by the presence of more than one black square in a row. This implies that from one processor more than one material flow leaves.

Control of this kind of structure is simple. In the example, the controller of processor A should decide if products should go to processor B or to processor C.

Convergent structure





Example 3.

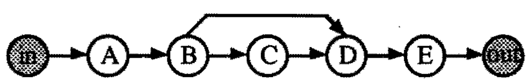
A convergent structure can be identified by the presence of more than one black square in a column. This implies that one processor receives material flow from more than one processor.

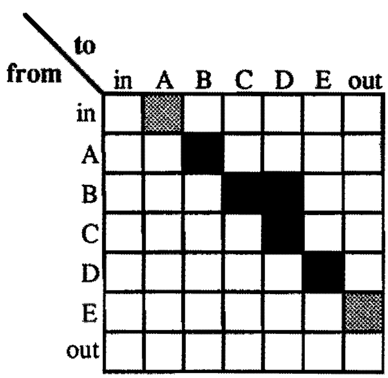
Two situations can be distinguished. The convergent processor (processor E in the example) can be an assembly processor. This processor then needs material input from all input processors (processor B and D in the example) for its proper operation. Control should be directed towards the simultaneous ('just-in-time') delivery of both material flows.

The other situation arises if the converging processor is a processing processor. This processor needs material input from one of the input processors. Control should be directed towards the proper scheduling of the converging processor.

The two situations can easily be identified if the icons proposed for processor-diagrams are used. Figure 4.7 shows these icons.

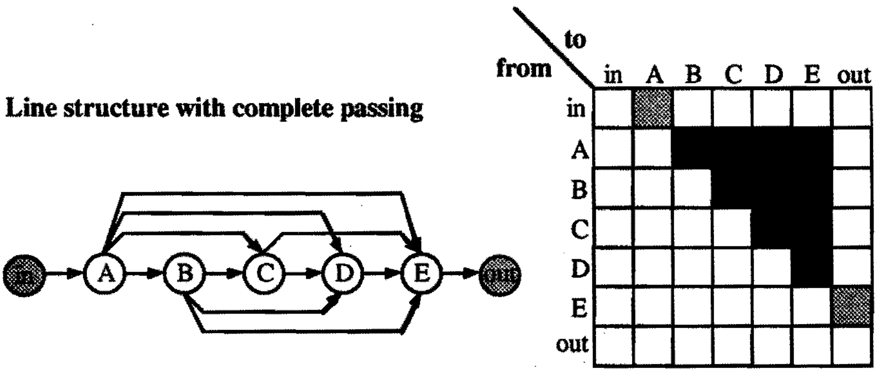
Line structure with passing





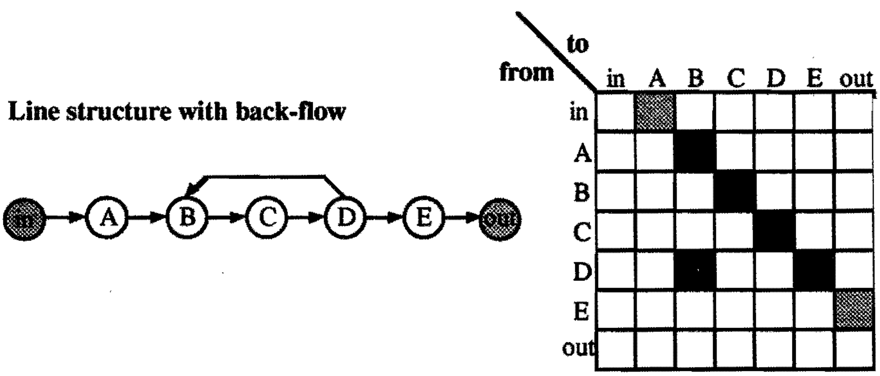
Example 4.

Passing is a special case of a combination of a divergent and convergent structure. This can be identified in the incidence matrix representation by the presence of more than one black square in a row as well as in a column.
The remarks made for the divergent structure and the convergent structure count for the line structure with passing as well. The two situations that exist in the convergent structure can also be identified in this structure, although the assembly variant is less likely to occur.



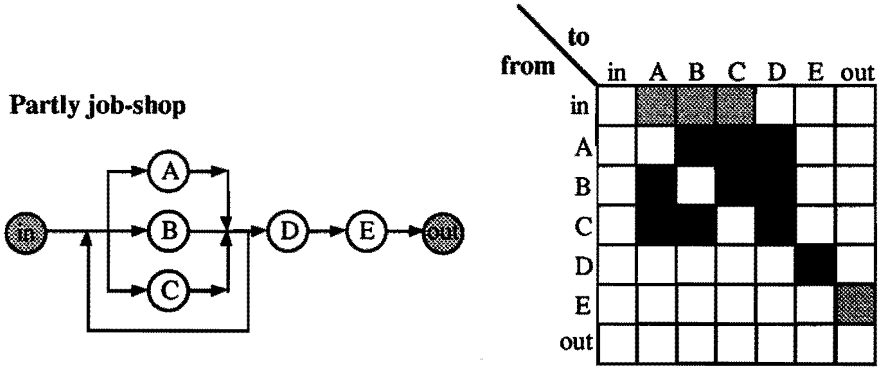
Example 5.

If the top right triangle of the incidence matrix is totally filled, the structure can be identified as a line structure with complete passing. This situation is not very likely to occur. The remarks made for the previously discussed structures count for this structure too. Control will be more complex, since more scheduling is required.



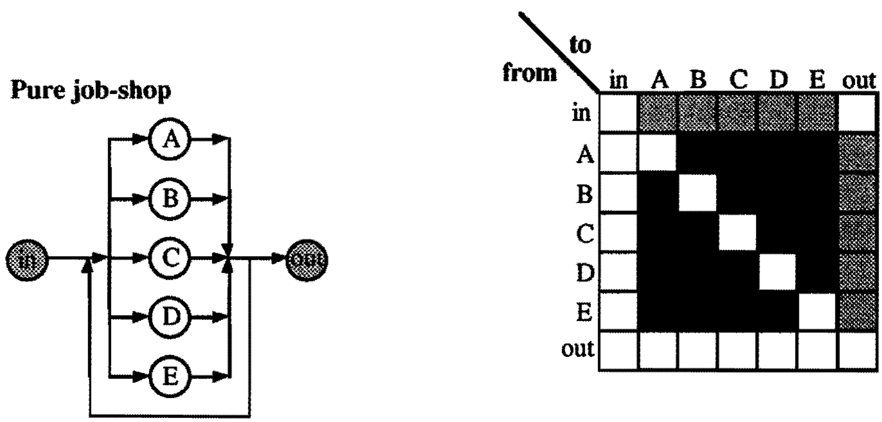
Example 6.

So far, the incidence matrices belonging to the structures did not contain black squares in the bottom-left triangle. The presence of a black square is this part of the matrix indicates a black flow. Control of back flow structures is more complex than the control of flow structures (no squares in the bottom-left triangle), because of the cyclic nature of the structure. Scheduling becomes more difficult.



Example 7.

The structure becomes even more complex if part of the structure has no preferred processing sequence at all. This can be identified in the incidence matrix by the presence of two similarly filled parts mirrored in the TLBR diagonal.
Control of this kind of structure is complex.



Example 8.

The most complex structure is the job-shop. No preferred processing sequence can be identified whatsoever. If the matrix is totally filled (except the TLBR), the structure can be identified as a pure job-shop.

Control of this kind of structure is most complex, because of the highly cyclic nature of the structure.

Remarks

The complexity of a production structure can be derived from the incidence-matrix. The complexity of the control system is related to the complexity of the production structure. The most simple production structure contains only squares adjacent to the TLBR diagonal of the matrix. The control system that is required to control this system is most simple. The complexity of the control system increases with increasing complexity of the production structure.

The complexity of a production structure therefore increases if more squares are introduced in the top-right triangle of the matrix. The complexity of the production structure further increases if squares are introduced in the bottom-left triangle of the matrix. The most complex situation exists if the entire matrix is filled with squares. This situation is called a job-shop.

Appendix B. Empirical Test

Chapter 5 describes an empirical test of the structured design approach. Detailed information on the empirical test is treated in this appendix. Firstly, the assignment that has been given to all sixteen designers will be presented. Secondly, the literature the designers used during the design process will be mentioned. After this, the instructions given to the designers will be presented. Finally, the behaviour in time of all sixteen designers will be presented. Chapter 5 only showed two examples of these graphs.

B.1. Assignment

An English translation of the original assignment will be presented giving the most essential information.
Firstly, some general information on TU-PLAST is presented. Some of its history and the growth of the turnover from 14 million Dutch guilders in 1986 to 30 million guilders in 1990 is mentioned. A continuing growth of 20 % a year is expected for the future three years.

Products
The products produced by TU-PLAST can be divided into two groups:

1. consumer goods
2. industrial products

The consumer goods are dived into five series:

1000 series: hooks
2000 series: mirrors
3000 series: caps, door protectors, tap hoses
4000 series: bathroom products
5000 series: kitchen products

The products in the 3000 series are manufactured in an immersion bath. The remaining consumer goods are manufactured using injection moulding.
Series 6000 contains the industrial products. These can be manufactured by either injection moulding or immersion.
Consumer goods are manufactured on stock, whereas industrial products are made to order.

Drawings of all product types have been supplied. The amounts of product manufactured, their selling price and their turnover has been supplied for all product types.

Production

The various production departments and service departments are presented. Besides this, also the capacities of all equipment in the production departments are given. The steps in the production process of all product types are also given. The current floor-plan has been supplied.

Problem Statement

The management expects that TU-PLAST in the near future will not be able to satisfy market demands. Delivery times and product prices will remain under great pressure. Production departments, therefore, need to be redesigned or optimised.

Assignment

Redesign TU-PLAST. Nothing of the product design can be changed. The control of the manufacturing does not need to be designed.

B.2. Literature

The literature studied and used by both groups was equal with two exceptions: two extra articles were supplied to group A.

Literature for both groups:

- Kalpakijan [1991]
- Buffa and Sarin [1987]
- Van Der Mooren [1984]
- Balkestein, Erkelens, Langemeijer, Schrauwen [1987]

Extra literature for group A:

- Brandts [1993a]
- Brandts [1993b]

B.3. Instructions

Instructions for both groups were equal with the exception of the literature that could be used (see above). A translation of the instruction will be presented below.

Start design process:	9.00 am
Pause:	12.30 pm - 1.30 pm
End design process:	4.30 pm

Literature that can be used in the design process: see above.

Try to follow the material discussed in the lecture as much as possible.

Notes during the design process
The chronological order of the design process must be traceable. Therefore, do not change anything in your notes, but use a new piece of paper and refer to previous notes or drawings, etc.
The following things need to be noted:

time in the left margin, each time the time is announced (every half hour)
thoughts and reflections, while making design decisions
design results, drawings, diagrams, etc.
calculations
questions and answers to questions

Possible ways to organise your notes:

thoughts and reflections on different paper than drawings, etc.
thoughts and reflections on left side of the paper, drawings, etc. on the right
thoughts, reflections and drawings, etc. together

Communication on the design or the design process with other designers is not permitted until 4.30 pm.

Questions should be submitted in writing, provided with your code name. Incorporate the questions and their answers, with the appropriate time, in your notes.

B.4. Behaviour in Time

Chapter 5 showed two examples of the behaviour in time. Two examples from each group has been taken. Below, the behaviour in time of all sixteen designers is presented. Firstly, the legend to the figures is presented.

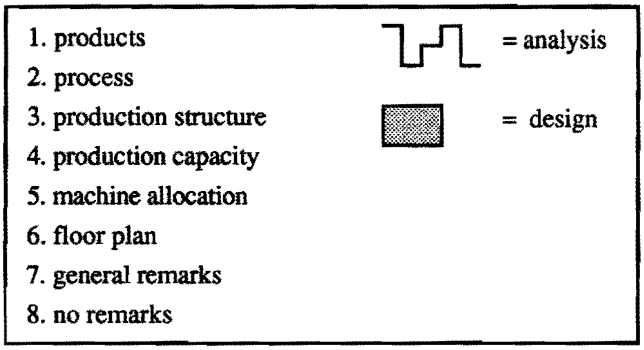


Figure B.1. Legend to the figures below.

A1

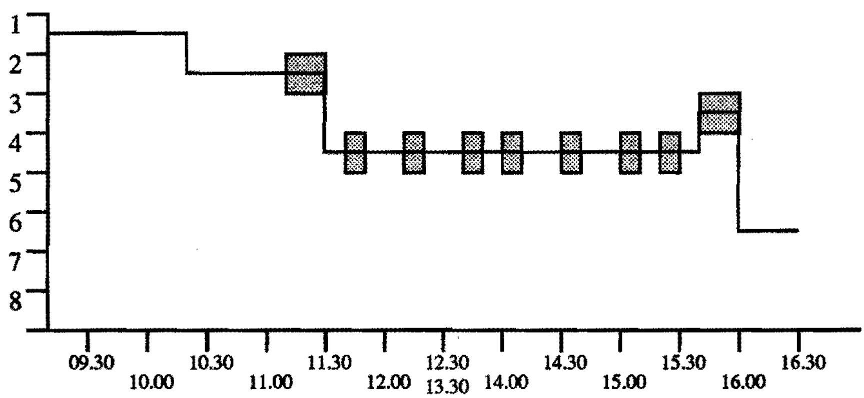


Figure B.2. The behaviour in time of designer A1.

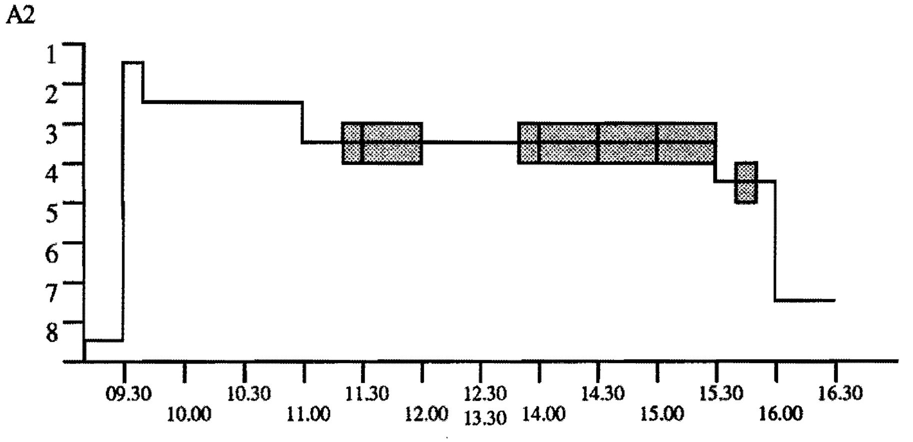


Figure B.3. The behaviour in time of designer A2.

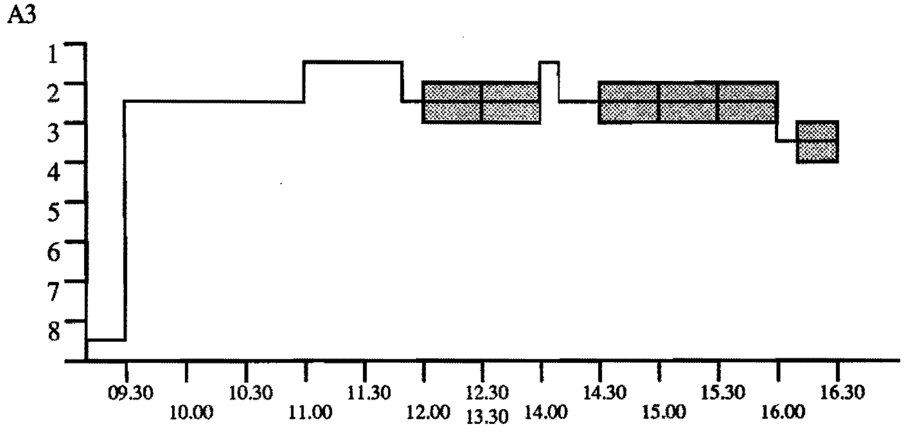


Figure B.4. The behaviour in time of designer A3.

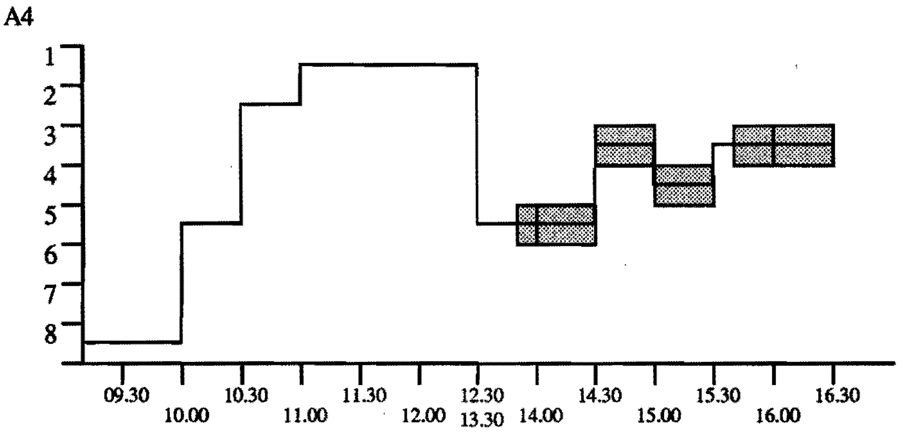


Figure B.5. The behaviour in time of designer A4.

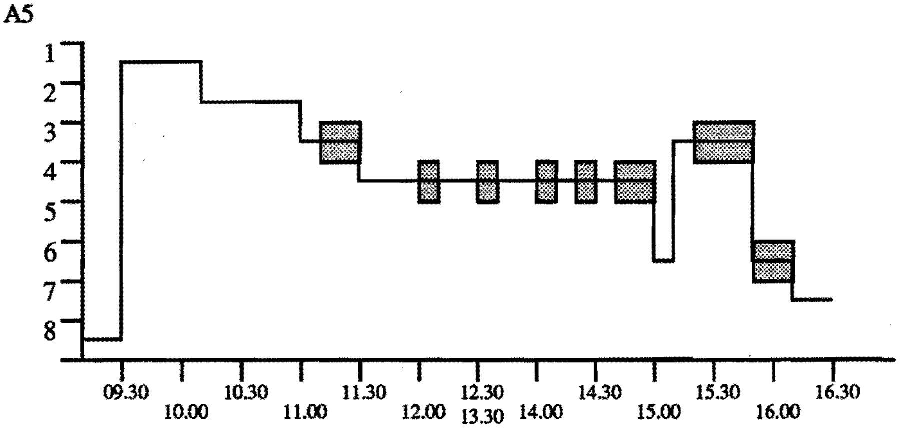


Figure B.6. The behaviour in time of designer A5.

A6

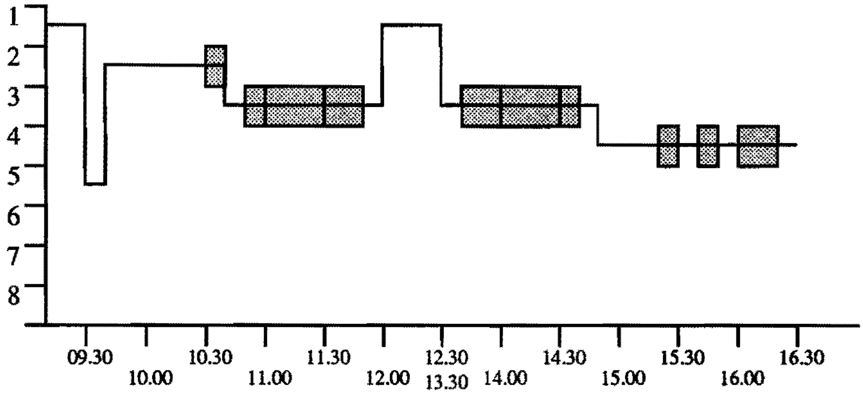


Figure B.7. The behaviour in time of designer A6.

A7

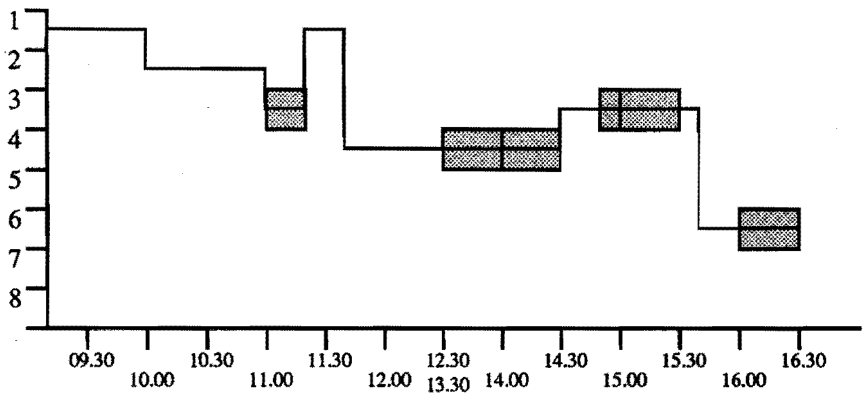


Figure B.8. The behaviour in time of designer A7.

A8

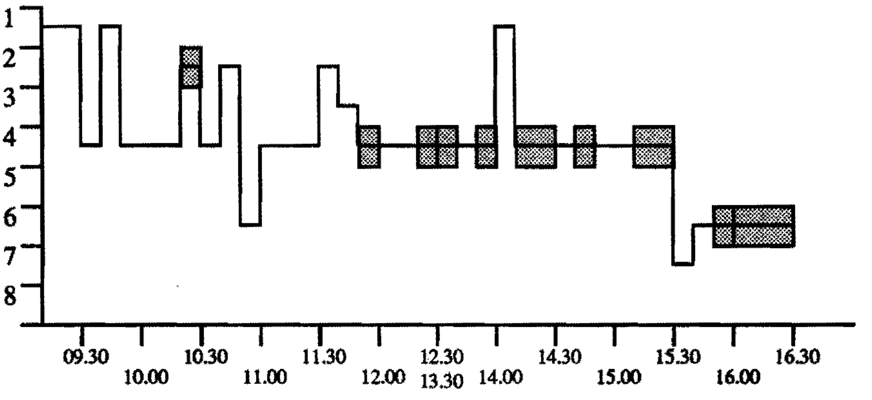


Figure B.9. The behaviour in time of designer A8.

B1

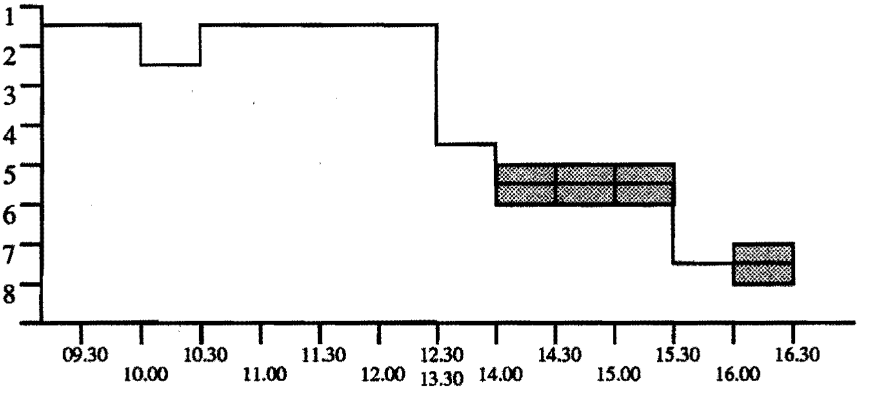


Figure B.10. The behaviour in time of designer B1.

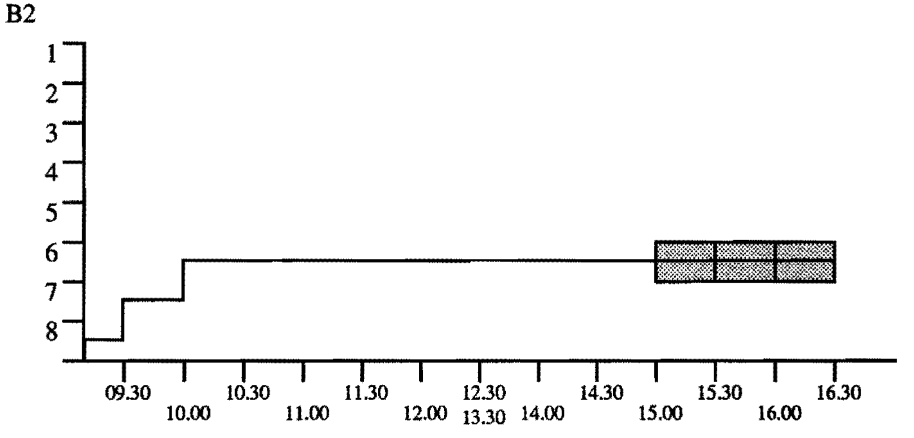


Figure B.11. The behaviour in time of designer B2.

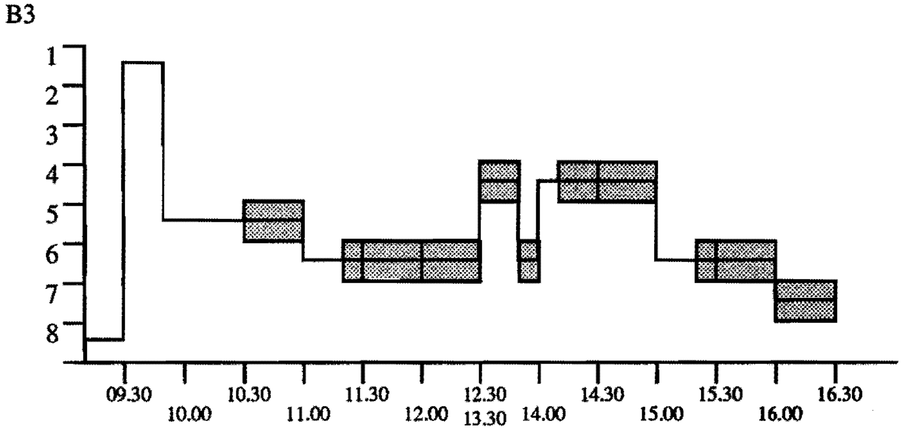


Figure B.12. The behaviour in time of designer B3.

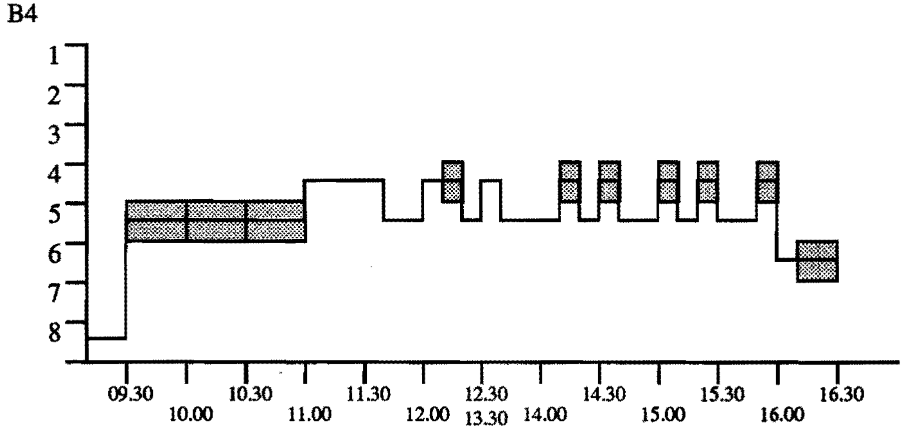


Figure B.13. The behaviour in time of designer B4.

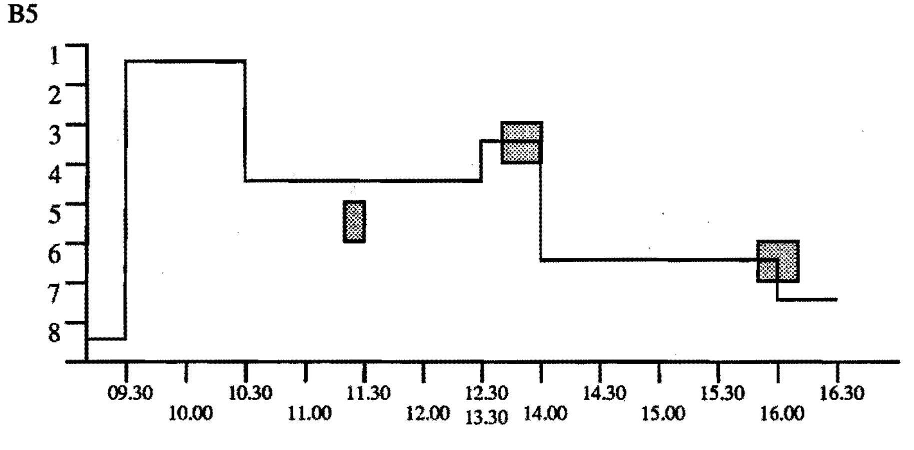


Figure B.14. The behaviour in time of designer B5.

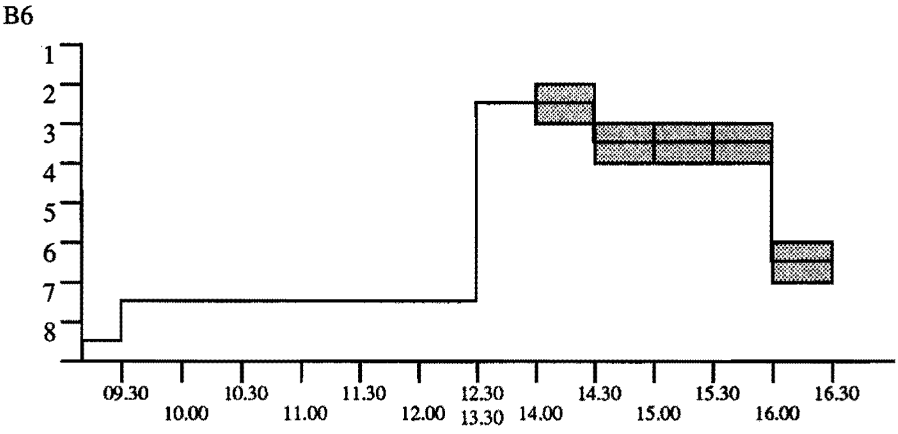


Figure B.15. The behaviour in time of designer B6.

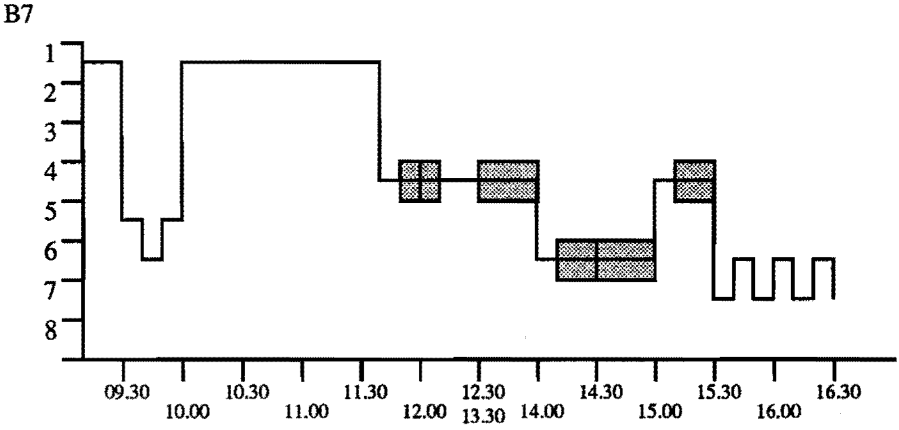


Figure B.16. The behaviour in time of designer B7.

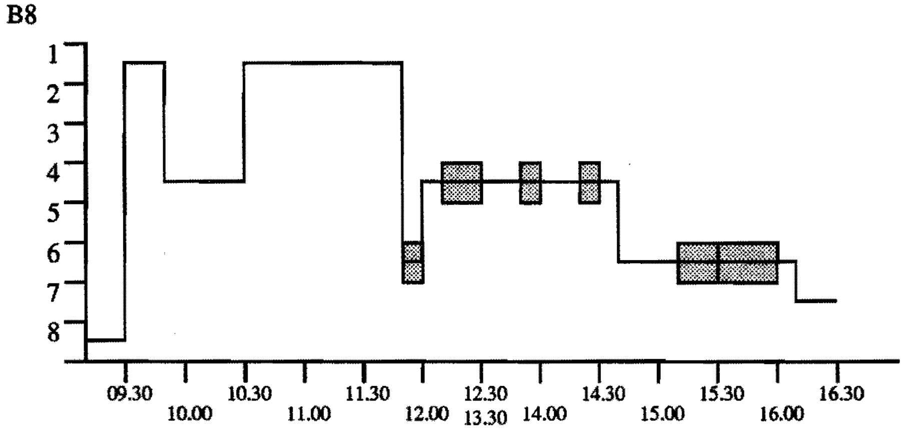


Figure B.17. The behaviour in time of designer B8.

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Curriculum Vitae

Luc Brandts was born in Maastricht, The Netherlands on the 28th of September, 1966. From 1977 to 1984 he attended the St. Maartens College in the same city. After finishing his Gymnasium β, he started his studies in Mechanical Engineering at Eindhoven University of Technology.
The final years of his study he specialised in the modelling and design of industrial systems in the section Production Automation of prof.dr.ir. J.E. Rooda. He graduated in 1989 on a research project on the modelling and simulation of the goods flow in hospitals. On December the 25th 1989, he started his research project on the design of industrial systems.

Together with Tim Willems, he founded Brandts & Willems Intelligent Systems Engineering (*BWISE*), a company specialising in the methodical (re-) design of products and production systems as well as the application of intelligent techniques in industrial system design and control.

Stellingen

behorende bij het proefschrift

Design of Industrial Systems

L.E.M.W. Brandts

9 december 1993

1. Le tout sera fait avec ordre et méthode.
   Napoleon Bonaparte in 'Oorlog en Vrede', Leo Tolstoj

2. Een methode is in het rijk van de geest te vergelijken met een kruk. De ware denker loopt vrij.
   Bill Clifford in 'De avonturen van Bill Clifford', Godfried Bomans

3. Het belangrijkste in ieder ontwerpproces is de formulering van het doel.
   dit proefschrift

4. De kennis benodigd voor het ontwerpen van een fabriek kan niet in één persoon verenigd zijn.
   dit proefschrift

5. De bezettingsgraad van een machine, afdeling of fabriek beoordeelt niet de prestatie van deze machine, afdeling of fabriek, maar hooguit de prestatie van de investeringspolitiek in het verleden.
   dit proefschrift

6. Hoewel soms produktief, is iedere classificatie of indeling een discretisatie van een continuüm en als gevolg hiervan arbitrair.

7. Zolang zogenaamde eye-openers, zoals 'if you need a computer to run your business, then hope your competitors need one too', daadwerkelijk de ogen van managers openen, blijft er ruimte voor management adviseurs met meer gevoel voor taal dan voor fabrieken.

8. Een groot deel van het vakgebied der marketing houdt zich bezig met, liefst Engelstalige en mogelijk allitererende, herformuleringen van het aloude 'de klant is koning'.

9. Totdat serieus onderzoek anders uitwijst, dient de veelgehoorde stelling dat proefschriften vroeger van een hogere kwaliteit waren dan tegenwoordig te worden beschouwd als een variant van de stelling dat de winters vroeger strenger waren.

10. Hoewel het bestaan van God niet kan worden bewezen, kan het bewijs voor diens gevoel voor humor eenvoudig worden geleverd door te wijzen op het bestaan van het neusaapje (Nasalis larvatus).

11. Hoe groot de rampen in de wereld ook mogen zijn, het weer zal altijd deel uitmaken van het Nederlandse journaal.

12. Voor velen wordt het milieuprobleem pas echt nijpend als ademhalen adem halen wordt.

Luc Brandts