Engineering work within the factory of the future

Baaijens, Roeland

Award date:
1991

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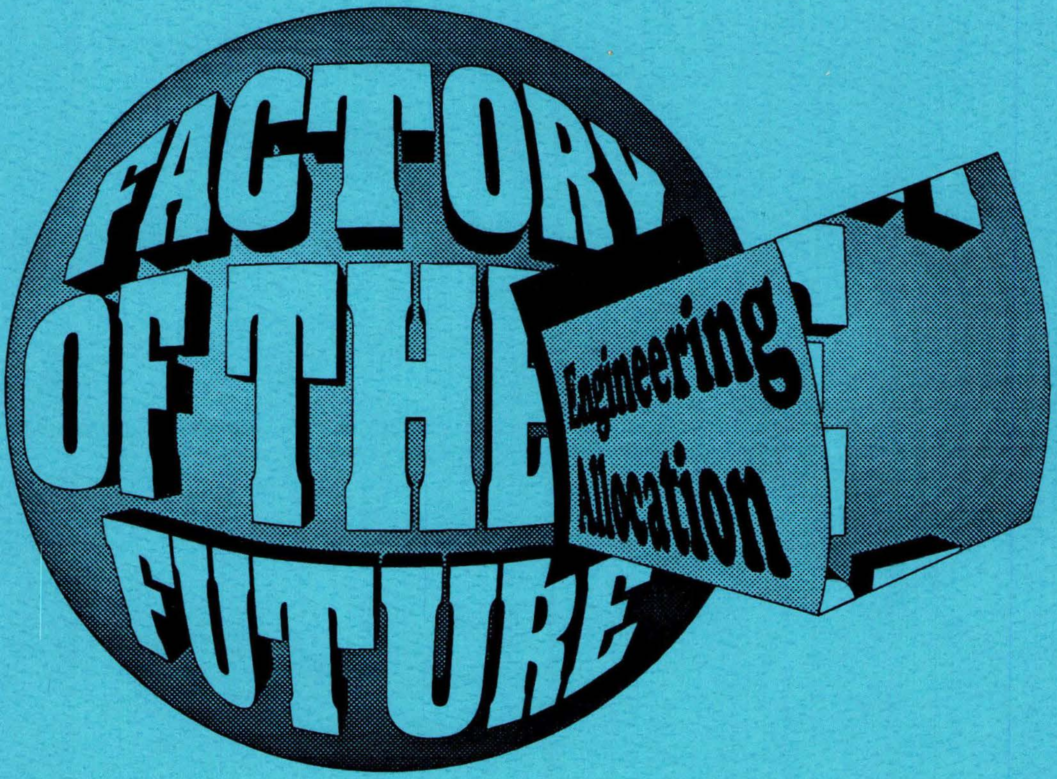

Roeland Baaijens
Department of Industrial Engineering
& Management Science
Eindhoven University of Technology

Eindhoven, November 1991.

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FOREWORD

This report is composed as a part of my master project on the study of Industrial Engineering at the Eindhoven University of Technology. The master project is the final part of the study and has an average duration of nine months. It is meant to give the student the opportunity to show his understanding and ability about the knowledge he has achieved during the study to practical situations. On completion of the entire master project a final report and an article must be written, to be defended at an open presentation.

I performed my master project within an European project. This project is called "Factory Of the Future" and it is an ESPRIT Basic Research Project. Seven European universities and institutes participate in the FOF project.

I fulfilled my tasks within the FOF project at the SINTEF research institute in Trondheim, Norway, one of the seven members of the project consortium. The guidance from SINTEF was given by J.O. Strandhagen and from the TUE by Prof. Bagchus, first supervisor, and from Prof. Wortmann, second supervisor. I would like to thank these people for their guidance and support during the project that made it possible to fulfil my masters. I also want to thank my two editors, Stephen and Paddy, for their English input (so if you find any mistakes, you know the source) and all other people who made it possible that my master project has been ten months of "quality time".

Roeland Baaijens

ABSTRACT

This master report "Engineering work within the factory of the future", describes the development and implementation on a computer system of an industrial engineering scientific model within the ESPRIT Basic Research Action nr. 3143, Factory Of the Future, concentrating on the engineering work.

SUMMARY

This report discusses the work done on the FOF project for the master project "Engineering work within the factory of the future". This means that the report focuses on the FOF project where the engineering work is concerned. The report discusses not only the engineering work but also the distribution of particular tasks in an organization. This distribution is applied more to the manufacturing and assembly department than to the engineering department.

"Factory of the future" (FOF) is the name of the ESPRIT Basic Research Action nr. 3143. The project is a cooperation between seven European universities and institutes. The title of the FOF project is:

> "Towards an integrated theory for design, production and production management of complex, one of a kind products in the factory of the future"

The ultimate goal of the research is obtaining a designer's workbench for the development of Computer Integrated Manufacturing (CIM) in one of a kind production (OKP) systems. For developing an integrated theory on OKP systems, different views on CIM were investigated. Studying these views led to the development of eleven so called "*drawing models*". In later stages of the master project these models had to be integrated and implemented on the FOF workbench.

The objective of the master project as formulated in January 1991, looks as follows:

> "The development and implementation on a computer system of an industrial engineering, scientific model within the factory of the future project, concentrating on the engineering work"

This objective resulted in the following four tasks:

1. Developing a drawing model concentrating on the engineering work in OKP systems.
2. Defining interfaces with other drawing models, especially the model developed at the SINTEF institute in Trondheim where this master project has been performed.
3. Testing of the relationships of the developed model in companies producing one of a kind products.
4. Defining a particular case to implement the model on the FOF demonstrator.

Before discussing these tasks, the way FOF describes (the design of) OKP systems is explained.

FOF distinguishes two major kind of variables. The first kind are the so called *design choices* (DC's). Design choices are the choices to be made ("the knobs to be turned") in designing an OKP system. The second kind of variables are the *performance indicators* (PI's). Performance indicators evaluate the performance of the system after the design choices are set.

All relevant design choices and performance indicators for (re-)designing an OKP system are brought together in the DCPI network. In this network the relationships between the design choices and performance indicators are roughly defined. This means that the DCPI network represents the theory concerning OKP systems at a high level of abstraction. The DCPI network is therefore part of the reference level of the FOF conceptual framework.
The second level of this framework is called the particular level. On this level so called drawing models, which highlight some design choices and some performance indicators of the DCPI network, can be filled in for particular real-life cases.

For developing the "Engineering Allocation model" existing theories were studied. These theories, however, were found to be fragmentated and not applied towards OKP systems. Most of these theories also lacked empirical evidence and were not operationalized.
From the theoretical backgrounds described in the report and through discussion with my supervisors, the Engineering Allocation model was developed. Four design choices are distinguished in this drawing model:

1. The engineering effort invested in defining the functional requirements.
   The functional requirements show the wishes, needs and demands of the customer.
2. The engineering effort invested in reducing the number of new parts of "type 2".
   New parts of "type 1" are parts which have certain quality or costs advantages over the range of standard parts. New parts of "type 2" do not add a value to the entire range of parts produced by the company. These parts are also not cost reducing.
3. The engineering effort invested in avoiding engineering rework.
   Engineering rework is the work which has to be done more than once by the engineers responsible for the design and construction, because a developed part is not feasible or because mistakes in the drawings or specifications make production impossible.
4. The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization

The following performance indicators are related with the four design choices:

1. The engineering throughput time
   The time needed for information to complete the design and construction stages
2. The manufacturing and assembly throughput time
   The time taken to complete a production order, starting at the moment when materials are ready for the first operation, and finishing with the completion of the last operation of the order
3. The required human capacity
   The required number of people to realise the required amount of work they are responsible for within a defined period of time
4. Labour costs
   The required number of people times the wages of these people
5. Job quality
   To have within the job content the opportunity to:
   - regulate the output of the process, if there are changes in either the input or throughput of the process
   - introduce changes in the process, to adapt to another environment

- achieve the same results in several ways

6. The costs of work in process
   The material costs of the work in process
7. Training costs
   The costs needed to train employees in certain capabilities
8. The costs for machines and tools
   The costs needed to buy required machines and tools
9. Product quality
   How far the variation in size, weight, shape, finish, and so forth for products or services are maintained within given limits

After completing the model, the relationships between the variables of the model were tested in OKP-companies. This was not an empirical validation in the strict sense but more a gathering of opinions of some experts from industry. This testing resulted in two main conclusions:

1. Indications were given that the relationships as they are modelled are present in industry
2. Indications were given that the relationships as they are modelled were found to be relevant to engineering work within OKP systems

The implementation of the model on the FOF demonstrator and the development of an interface with another FOF model, namely "The Order Release Model" were the remaining tasks of the master project. These two tasks were later combined into one task.

The FOF demonstrator is a software tool which can demonstrate the models developed within FOF by means of one common case (particular model). Different computer tools were used to implement the Engineering Allocation model on the FOF demonstrator. The simulation package STELLA was used to implement the main part of the model. To model some specific parts of the Engineering Allocation model the simulation program SIMMEK was used. Some results from the simulation in SIMMEK were used as input to the STELLA model. SIMMEK is a computer based discrete event simulation tool for performing analysis on a manufacturing system. It was developed at the production engineering department of the SINTEF institute in Trondheim. This simulation tool has also been used by the Order Release model, the other FOF model developed in Trondheim. It was agreed upon the use of the same SIMMEK model for the FOF demonstrator. This is the interface between these two models. The Engineering Allocation model uses some results from the simulation runs in SIMMEK as input to the STELLA model.
The STELLA model covers the entire Engineering Allocation model. STELLA is a simulation package which is commonly used within the FOF project. Because of the limited time available it was not possible to integrate the SIMMEK model with the STELLA model so that input for STELLA was derived automatically from the SIMMEK model.
Another interface, between all eleven FOF models, is the common user interface of the FOF demonstrator. All the models have the same entry screens and they use the same template for presenting the design choices and performance indicators.

INTRODUCTION

"Engineering work within the factory of the future" is the title of this master report. The master thesis is a part of the "Factory Of the Future" (FOF) project. The greater part of this master thesis has been performed in Trondheim, Norway. Some parts of the master project have been performed in Bremen and Eindhoven.

In this section of the report an introduction of the FOF project is given. Chapter one discusses the objective and task formulation of the master project. In the second chapter the terminology commonly used in the FOF project is presented. The theoretical backgrounds and a description of the developed model follow in chapter three. In the fourth chapter the implementation of the model is described. The conclusions and recommendations are presented in the last chapter.

FOF is the name of the ESPRIT Basic Research Action nr. 3143. The title of the FOF-project is [1]:

"Towards an integrated theory for design, production and production management of complex, one of a kind products in the factory of the future"

The FOF project is an European project with seven partners, listed in table 1, and is concerned with a consistent theory for one of a kind production (OKP).

TUE	Eindhoven University of Technology Faculty of Industrial Engineering	The Netherlands
BIBA	Bremen Institute for Industrial Technologies and Applied Work Science at Bremen University	Germany
GRAI	Universite de Bordeaux 1 Laboratoire de Productique et d'Automatique	France
HUT	Helsinki University of Technology Institute of Industrial Automation	Finland
SINTEF	Production Engineering Laboratory Trondheim - NTH	Norway
DTH	Technical University of Denmark, Lyngby Electric Power Engineering Department	Denmark
CIMRU	University College, Galway CIM Research Unit	Ireland

Table 1: The members of the FOF consortium

The ultimate goal of the FOF research project is to obtain a designer's workbench for the development of Computer Integrated Manufacturing (CIM) in OKP systems. Two conditions have to be fulfilled before the designer's workbench can be developed. The first condition is a *method to describe* the operations in the OKP factory. These operations include design, tendering, logistics, quality control etc. The second condition is an *integrated theory* of how to redesign an OKP factory.

The existing description methods and theories about the (re)design of a factory are fragmentated in two ways:

- First, there is a fragmentation in production phases. Design, process planning and manufacturing have all become "computer-aided". CIM indicates the effort to cross the boundaries between these phases.

- Second, there is a fragmentation in views on CIM. A production-oriented view differs from an organizational or human oriented view. The project tries to unify these fragmented theoretical parts into one whole.

Originally each partner in the project studied one specific view [2]. These seven views are:

1. The operations research and cybernetic view
2. The human centred view
3. The communications oriented view
4. The databases view
5. The functional view
6. The organisational view
7. The linguistical view

Later on these seven views were found overlapping and this led to a reduction to three different views. The three views which reflect the major different design objectives are:

1. The workflow view
2. The resources view
3. The organisational/decisional view

In the next phase of the project, models were developed to highlight different aspects of the views. Some of these models have interfaces to each other and all models are implemented on the FOF demonstrator (earlier called designer's workbench). The FOF models are listed in table 2.

Model Name	Developer	Institute
1. Aggregate Production Control	P. Hoben	CIMRU
2. Cross Impact Analysis Model	H. Boehling	BIBA
3. Customer Order Acceptance Model	P. Malany	CIMRU
4. Departemental Control	F. Marcotte	GRAI
5. Economic Model	J. Nikkola	HUT
6. Engineering Allocation Model	R. Baaijens	SINTEF
7. Group Design Model	P. Breuls	BIBA
8. Human Resource Management	B. Hamacher	BIBA
9. Inter-Departemental Control	P. Timmermans	TUE
10. Order Release Model	J. Strandhagen	SINTEF
11. Simultaneous Engineering Model	B. Sederholm	HUT

Table 2: The FOF models

The interim results of the FOF project have been presented in reports of the five work packages. In the first work package, current theory for describing operations in production systems was examined, ordered and described.
In the second package, an unified description model was developed. This is what is known in FOF terminology as the conceptual model and it is multi-disciplinary.
In the third package, existing workbenches (specifications, methods, tools, languages) for implementation of the conceptual model were selected.
In work package four the conceptual model was partly operationalized to make it suitable for the design of real-life or simulated production systems.
The last package is concerned with the demonstration of the conceptual model by application to a simulated industrial test-case.

The results of the project, the FOF demonstrator and the theories developed within FOF, have been presented at the IFIP conference at the BIBA institute in Bremen between November 12-14, 1991.

CHAPTER 1: OBJECTIVE AND TASK FORMULATION

Introduction

The objective, task formulation and realised time planning of the master project are presented in this chapter. The terminology used in the objective and task formulation will maybe not be totally clear, but this will be explained extensively in the following chapters. Some of the terms are already explained in the introduction.

Objective and task formulation

The objective of the master project as formulated in January 1991 looks as follows:

> **"The development and implementation on a computer system of an industrial engineering, scientific model within the factor of the future project, concentrating on the engineering work"**

This objective resulted in the following four tasks:

1. Developing a drawing model within the workflow view concentrating on the engineering work in OKP systems.
2. Defining interfaces with other drawing models, especially the Order Release model.
3. Testing of the relationships of the developed model in an OKP environment.
4. Defining a particular case to implement the model on the FOF demonstrator.

The four tasks mentioned have been roughly executed in the sequence as they are stated here. Notwithstanding the fact that some parts of the tasks have been executed in a parallel and iterative process.

Time planning

The nature of the FOF project, basic research, makes it very difficult to work with a tight time schedule. It is also very difficult to work with a tight time schedule for the master project, as the master project is performed within the FOF project. I will mention three reasons why it was so difficult to present a tight time schedule at the start of the master project.
First, the continuation of the master project depends on the interim results of the FOF project (It is very hard to plan the results of a basic research project with seven partners, each holding different views).

Second, the communication between the partners causes some difficulties (It takes a long time before everybody receives and responds to messages).
Third, final appointments with companies to test the relations of the model (which still had to be developed at the beginning of the project) were not made and this led to some problems during the continuation of the master project (Section 3.5).
For these reasons a realised instead of a planned time schedule is presented here.

Time period	Subject
14 Jan. - 1 Feb.	Introduction period, becoming familiar with the FOF project, studying literature about FOF and engineering
2 Feb. - 15 Mar.	Development of the Engineering Allocation model
16 Mar. - 29 Mar.	Development of a first prototype of the implementation of the model
30 Mar. - 20 Apr.	Joined work on the implementation of the FOF models in Bremen
21 Apr. - 24 Apr.	FOF workshop in Bremen
25 Apr. - 29 Apr.	Preparation for the interim presentation in Eindhoven
30 Apr. - 6 Jul.	Further development of the Engineering Allocastion model and attempts to find a company to test the relations of the model
7 Jul. - 10 Jul.	Meeting of the FOF model developers about the required documentation
11 Jul. - 2 Aug.	Documentation for work package 5
3 Aug. - 15 Aug.	Implementation of some parts of the model in SIMMEK
16 Aug. - 1 Sep.	Holiday
1 Sep. - 27 Sep	Implementation of the model in STELLA and finishing the documentation
28 Sep. - 30 Oct.	Writing report master project

Table 3: Realised time schedule of the master project

CHAPTER 2: FOF TERMINOLOGY

Before discussing the contents of the Engineering Allocation Model, the terminology which is commonly used within the FOF project should be stated clearly. The terms which are presented here will be used through the entire report.

Within the FOF terminology [2] several kinds of variables are distinguished. The most important variables are presented here.

First, *Design Choices* (DC's) are distinguished. These variables are the input of the (re)design of the factory. They are the choices made during the (re)design process ("the knobs to be turned"). The design choices are divided into two categories:

1. *Structural DC's* define completely the production system as such: the components of the production system and the relationships between these components. Some typical examples are: products, resources, production lay-out, decision rules and criteria.
2. *Operational DC's* define the input applied to the structural production system. Some examples are: customer orders, availability of subcontractors, working hours of the resources.

Second, *Performance Indicators* (PI's) are distinguished within the FOF terminology. These variables show the different performances of the system resulting from changes to the DC's. In redesigning the system, the structural DC's are changed. In testing the system the structural DC's are kept fixed while the operational DC's are changed and applied to measure different performances.

The third kind of variables are the *Intermediate Variables* (IV's). These variables show the connections between the DC's and the PI's. They are neither DC's or PI's and are only used in the calculations of PI's during testing of the system.

The last kind of variables are the *Situational Factors*. These variables are factors which influence the company, but the company is unable to influence these factors. Some typical examples are: the competitors, the market situation, the Gulf war.

To reflect the different major design objectives the model shown in figure 1 is considered from three different views. The three views are:

1. The workflow view
   A framework with theories about the appropriate way to structure the workflow through a factory. This workflow is not restricted to "physical" transformation of material. These theories lead to a structure of the workflow which is closely connected to an organizational structure in terms of departments, groups, task forces, teams, etc.

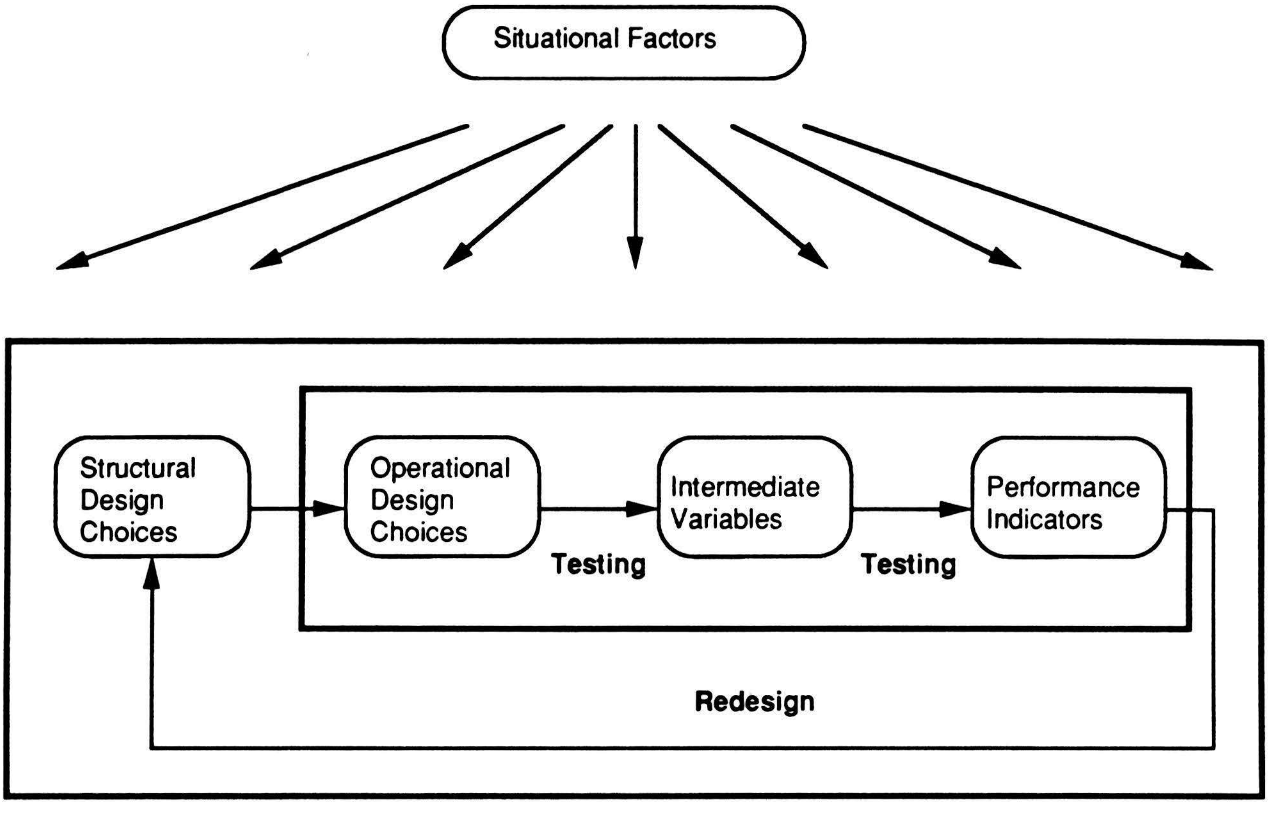

Figure 1: The variables and their relations

2. The resources view
   A framework with theories about the internal structure of the resources. In component manufacturing, this structure consists of the physical lay-out, the equipment, the task structure of individuals and groups. In OKP systems, and especially in an engineer to order situation, the human aspect seems to be most important.

3. The organizational/decisional view
   A framework with theories about decision making. In OKP systems it seems that the boundaries between decision making and other activities (such as design) are less strict than elsewhere.

The three views are integrated in a so called conceptual framework, shown in figure 2. This framework exists at two different levels:

1. The level of the *reference models*
   Reference models represent available theory. These models link general design choices via intermediate variables to general performance indicators.
   The reference models can also be split up into two sub-levels. The *primitive system* shows which objects (DC's, PI's, IV's) are distinguished. The *connectance model* shows the relationships between these objects. The connectance model is also known within the FOF project as the DCPI network (Design Choices - Performance Indicators network).

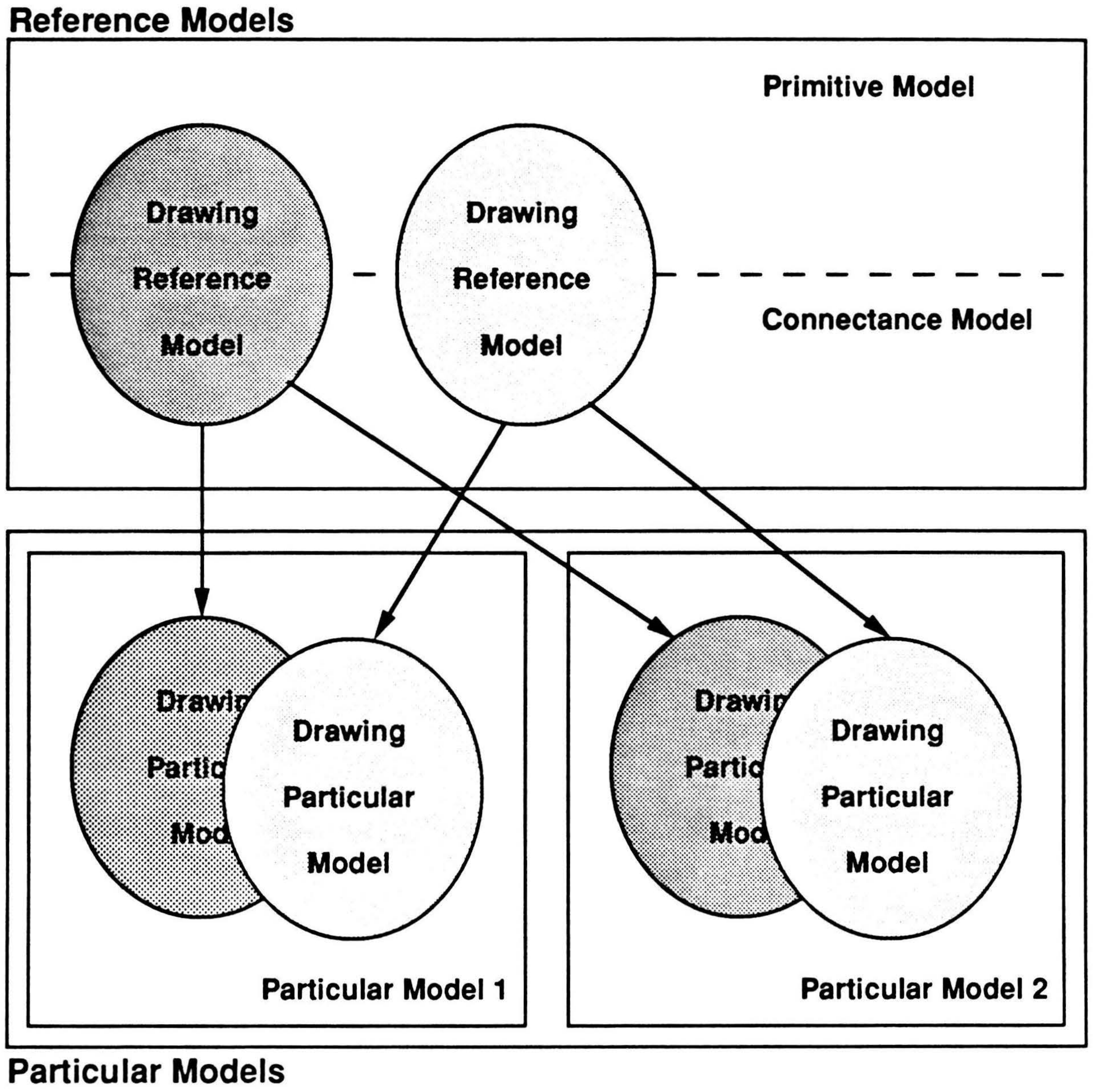

Figure 2: The conceptual framework

2. The level of the *particular models*
   Particular models represent an abstract example of a particular case or a real life situation. These models show particular design choices which have been made in a particular case. They enable the designer to specify alternatives for these design choices, and to calculate the consequences of these alternatives within a limited domain of knowledge.

On the two mentioned levels so called *drawing models* exist. A drawing model is a template for a particular real-life situation containing a limited number of DC's, IV's and PI's as well as well-known relationships between these variables. A drawing model may compromise a view, part of a view, or may even contain parts of several views.

On the reference level the model is called the *drawing reference model.* This model is a template for real-life situations and does not contain data of a particular case. It only shows general relations between the limited DC's, IV's and PI's which are distinguished in the model.

On the particular level it is called the *drawing particular model.* In this model the general relations are filled with data from a particular case. The relations are now specific for that case, and by changing the DC's this will give information about the PI's for that case.
This means that a drawing reference model can be filled with data from different cases and that different drawing particular models are created.
If several drawing particular models of one company are put together and relationships between these models are well defined, this is called a particular model. Such a particular model is the description of (a part of) a particular company in which the actual situational factors and the structural DC's have been set.

CHAPTER 3: THE ENGINEERING ALLOCATION MODEL

3.1 Introduction

In the first section of this chapter the workflow view and the second model of this view are briefly introduced, to give the reader a general insight into the project and the workflow view. The remainder of the chapter is concerned with the theoretical backgrounds, design choices and performance indicators of the Engineering Allocation model. Attempts to validate the Engineering Allocation model in "real-life" situations are described in the last part of this chapter.

3.2 The workflow view

The workflow view is defined as "defining and describing the workflow through the production system".
It is a framework with theories about the appropriate way to structure the workflow through the factory. This workflow is not restricted to "physical" transformation of material. These theories lead to a structure of the workflow which is closely connected to an organizational structure in terms of departments, groups, tasks forces, teams, etc. [2].

The first drawing model developed within the workflow view is the Order Release model. It has been developed by Jan Ola Strandhagen at the SINTEF institute in Trondheim. The title of the Order Release model is as follows:

> "A simulation model for investigating the risks and possible gains and losses involved with order release with uncertainty in OKP systems, based on the workflow view of the FOF project".

The model investigates different strategies for release of both manufacturing and engineering work orders in the factory. The strategies are investigated under different frame conditions like workload, percentage of OKP components, penalty costs etc.
The design choice of the model is the choice between an early release and a normal release of work orders. An early release means that the work order is released before the product specifications are complete. Since product specifications are not complete, uncertainty exists with what components to manufacture and produce in order that customised products may be manufactured.
A normal release means that the work order is released after the specifications have been made complete, meaning that the risk for the producer involved is much less. The release strategies concern:

- Engineering order release
- Purchasing order release
- Manufacturing order release

The performance indicators used in the model are:

- Delivery performance
- Inventory turnover
- Net profit

Given certain circumstances in OKP manufacturing, the model shows that an early order release strategy is superior to other strategies involving later release of manufacturing and engineering orders. The model is a typical example of a decision support model; it helps managers in their decision making.

3.3 Theoretical backgrounds

In this section the theoretical backgrounds of the Engineering Allocation model are presented. The description contains references to literature documenting existing theories.

Many theories exist which describe the effects of different organizational and communication structures on quality, costs, lead time etc. These theories however are fragmented and not applied towards OKP situations. Most of these theories lack empirical evidence, are not operationalized and show only very general effects. Almost no literature is found on OKP systems or on engineering in OKP systems. Under innovation, product development and engineering in general many theories exist. These theories were used and they were applied to the OKP situation.

Several authors note the lack of communication and mutual understanding between the different participants in product development. First, there is a lack of communication between customers and representatives of the company. Second, there is a lack of communication between the professionals of the different departments within the company during product development. Each order requires its own product development in an engineer-to-order environment. Existing methods and theories indicate the need for improvement concerning the area of the theories of the Engineering Allocation model.

McIntyre and McQuarrie [15] identify two communication areas which cause problems:

1. Companies are always in the process of loosing touch with their customers
2. Differentiated functions in a company are always in the process of loosing touch with one another.

The first "miscommunication" results in products which do not really fit to the customer requirements. For a company manufacturing customised products it is essential that products meet customer requirements. The second "miscommunication" results in problems during the development and production phases of the product.
The authors discuss "thought worlds", defined as "a self consistent outlook maintained both by task demand and membership in a social group". The thought world of the customer and of the departments of the company are different. This results in several communication problems. They stress the importance of communication between customer, marketing and sales and design and construction.

As the solution to the problems they advocate a program of customer visits. For companies with a small number of customers they advocate more intensive forms of partnering. Engineers play an important role in this program of customer visits or partnering. They are responsible for the product development. McIntyre and McQuarrie argue that sales and marketing people cannot fully represent the ideas of the customer to the product development engineers. They advocate that information passed between customers and product development engineers should not be filtered through the market function. Instead they propose direct contact between customers and engineers. Especially in the OKP-situation it is important that the product development is customer-order-driven. The need of communication between customer and engineer is paramount.

Love [14] indicates "the danger of the engineer riding his own hobby horse". He sees a tendency of engineers "to become enamoured with one's own creative solutions and to assume that it is what the customer wants".
He stresses the importance of the contact between engineer and customer to make sure that a product fits to the customer requirements. Love also considers the problems of filtered information between the engineer and customer if the sales or marketing departments play an intermediate role.
Love stresses the importance of communication between different departments within the company itself. He holds the view that "When something new is developed, personal communications supplement the specifications".

Kuronen did an initial literature study [13] for FOF on product development. She is the only author mentioned here, who analyses the OKP situation. She states that "the traditional way of organizing the product development process is to arrange it sequentially, one activity following the other. The process is not only sequential but also walled into separate development units. The different units work separately, throwing their part of the engineering work "over the wall". This creates costly problems which occur later in process development or manufacturing of the product. Feedback of the developed design to the product development department is not provided until testing of the prototype or the final product or not at all."
She also states that "the opportunity to save costs for a product which reaches the production phase is minimal and the costs of changes is maximal. The opportunity to save costs is greatest when the product is still at the conceptual level". One of the highest conceptual levels is the level of defining the functional requirements of the product together with the customer. At this level many different possibilities for configuring the product exist. By choosing standard solutions instead of developing new parts, when translating the functional requirements into technical specifications, uncertainties for costs, lead time and quality can be minimized.
In order that translation of functional requirements to technical specifications is devoid of any problems, it is important that technically qualified people are involved in the negotiation or cooperation with the customer.

She also discusses the problems of the communication between different departments and the lack of feedback between departments.

As a solution for problems mentioned here by Kuronen she advocates a process of simultaneous engineering. "This increases the amount of interactions between the different units. The total time spent on product development with a simultaneous engineering environment is more than the time spent within the traditional sequential engineering environment".

All authors focus on the need for communication and mutual understanding between the participants of the product development. As the FOF-project aims for an integrated theory instead of for a fragmentated theory, the product development is expanded to consider also the communication and organizational structure of the production and assembly department. The following theories are within the Engineering Allocation model only applied to the production and assembly departments and not to the engineering department. In later stages these theories can also be applied to the engineering department .

Van Assen, den Hertog and Koopman [4] use the following typology to distinguish between different organizational structures:

1. Process-oriented versus product-oriented
2. The extent to which help and staff-services are integrated with each other and with the production department
3. The number of hierarchical levels and the extent of delegation of tasks

The combinations of positions on each dimension defines for the larger part the communication, decisional and task structure of an organization. A choice of a certain communication structure for the product development should have consequences for the positions on the three dimensions.

For Burbidge [9,10] a product-oriented structure is equivalent to a group technology structure. "Clear production and assembly groups are identified in the group technology. A group is a combination of a set of workers and a set of machines or other facilities laid out in a reserved area, which is designed to complete a specified set of products or parts." He also describes how to make the transition from a process-oriented (functional) organization to a group technology organization. Burbidge focuses his discussions on the production and assembly departments. The extent to which help and staff-services are integrated with each other and with the production department is just discussed indirectly by Burbidge. But the principle of organization, groups responsible for a given family of parts or products, is used when organising groups of people in departments other than production. The number of hierarchical levels and the delegation of tasks is also discussed indirectly. Burbidge mentions the opportunity for delegation of tasks, but he does not discuss this point in greater depth.
Some of the main advantages of the group technology organization compared to the functional organization are:

- The planning and coordination will be simpler because each group is responsible for a particular family of parts or products
- The set-up time will reduce because a family of parts or products has more or less the same characteristics and thus standard setting of tools can be used
- The transportation time will reduce because almost no transport is required within one group

- It makes it possible to improve the job quality by involving operators in other tasks than only production
- The product quality will be improved because the product control circle is shorter

The second and the third dimension of the typology, i.e.

- The extent to which help and staff services are integrated with each other and with the production department
- The number of hierarchical levels and the extent of delegation of tasks

are discussed by van Amelsvoort and Kuipers [3]. According to these authors an organizations ability and need for communication are highly influenced by:

1. The distribution of tasks in a company
2. The organizational structure of a company.

They also advocate groups as basic organizational units but they use sociotechnical principles to defend their ideas. A group is defined as "a fixed group of multi-skilled people who are responsible for execution, control, evaluation, analyses and improvement of a complete production task and having sufficient resources for this task".

A family of parts or products, defined by the group technology, is a good example of a complete production task. Burbidge however is basically concerned about an organization based on families of parts or products giving an easier planning and a simpler production control system than in a functional organization, especially if this leads to reductions in throughput times, work in process and stocks. The sociotechnical view however goes beyond the view of Burbidge and advocates more responsibilities for the group members. Many tasks which normally are allocated to special staff or services are now allocated to the group. Following van Amelsvoort and Kuipers "Delegation of tasks for work preparation, planning, control, maintenance and repairs to a team of workers and involvement in personnel policy and product development improves the job quality and is the key to successful groups". Furthermore these authors describe the relation between the job quality and the quality of the organization.

3.4 The design choices and performance indicators

In this section the design choices and performance indicators of the Engineering Allocation model are discussed.
As stated before, many theories exist which describe effects of different organizational and communication structures on the quality, costs, lead time etc. These theories however, are fragmentated and not applied towards OKP systems. Most of the mentioned theories miss empirical evidence, are not operationalized and show only very general effects.
These general effects of design choices on performance indicators are shown in a reference model. In a drawing model however the relations between design choices and performance indicators should be more detailed.
From the theoretical backgrounds described above and through discussion with my supervisors four design choices were distinguished. These four design choices are related to nine performance indicators. In this section the design choices, the performance indicators and the relations between them are described.
The Engineering Allocation model is not restricted to the workflow view (Chapter 2). Aspects of the organizational/decisional view and of the resources view are also covered in the Engineering Allocation model.

3.4.1 The design choices

Four design choices are distinguished in the Engineering Allocation model. Three of these design choices are about the amount of engineering manhours used for communication between engineers and customers and between engineers and professionals of other disciplines within the company. The engineering manhours which are considered here are not solely put into communication, but also for example into working out proposals which are made during the communication.
The fourth design choice is concerned with the distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization. This last design choice and the theoretical backgrounds of this design choice are not applied to the engineering department. These theoretical backgrounds are within the Engineering Allocation model only applied to the manufacturing and assembly department. How these theories maybe can be applied to the engineering department is discussed in chapter 5.

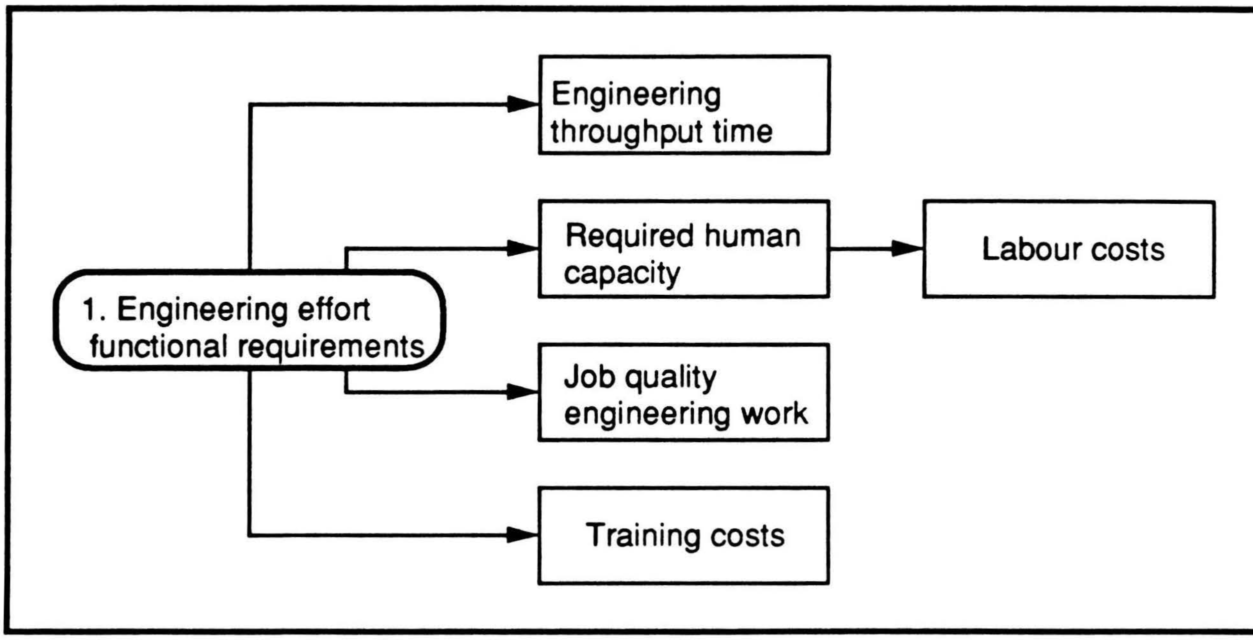

Figure 3: Relations between DC 1 and PI's

Design choice 1: The engineering effort invested in defining the functional requirements

This design choice defines the total amount of engineering manhours that on average is put into defining the functional requirements for one customer order.
The functional requirements are the wishes, needs and demands asked for by the customer. To get clear guidelines on what a customer requires, communication between customer, sales representative and engineer is required. An engineer is needed to understand the technical consequences of certain demands and wishes of the customer. The engineer knows the backgrounds of the functional requirements and this makes it easier for him to come with effective and efficient technical solutions. Filtered information between customer and engineer with the sales representative as intermediate is avoided. This will result in less changes on the product specifications by the customer during the product development, work preparation and/or even production of a customer order after that the functional requirements are fixed.

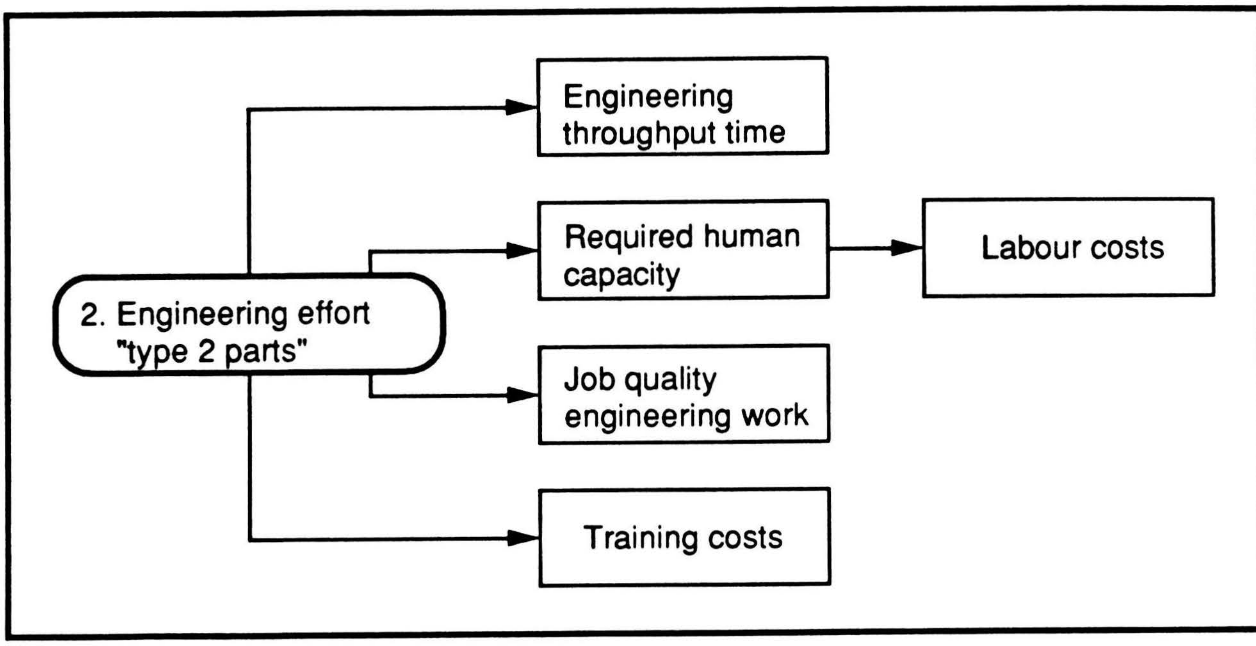

Figure 4: Relations between DC 2 and PI's

Design choice 2: The engineering effort invested in reducing the number of new parts of "type 2"

This design choice defines the total amount of engineering manhours on average put into one customer order to reduce the number of "type 2 parts".
In the Engineering Allocation model two types of new parts are distinguished. Both types of new parts require their own special design and construction.
New parts of "type 1" are parts which are initiated by a customer or by the company itself. These new parts have certain quality or costs advantages over the range of standard parts. "Type 1 parts" can often be used for more than one customer order and sometimes become standard parts.
New parts of "type 2" are parts which solely are caused by customer specifications. These parts will probably only used once and do not add a value to the entire range of parts produced by the company. These parts are also not cost reducing.
As new parts bring many uncertainties into the production system, these should be avoided for control reasons. The quality, costs and lead time of new parts are not known Therefore, if possible, it is preferable to use standard parts in the product. Main point however is that the functional requirements asked for by the customer are not affected. Thus the reduction of the number of "type 2 parts" requires cooperation between customer and engineer to assure that the functional requirements are not affected.
Reduction of the "type 2 parts" can also be achieved by working close together with purchasers and suppliers. It is possible that suppliers are able to deliver a standard part as the solution for a particular problem.

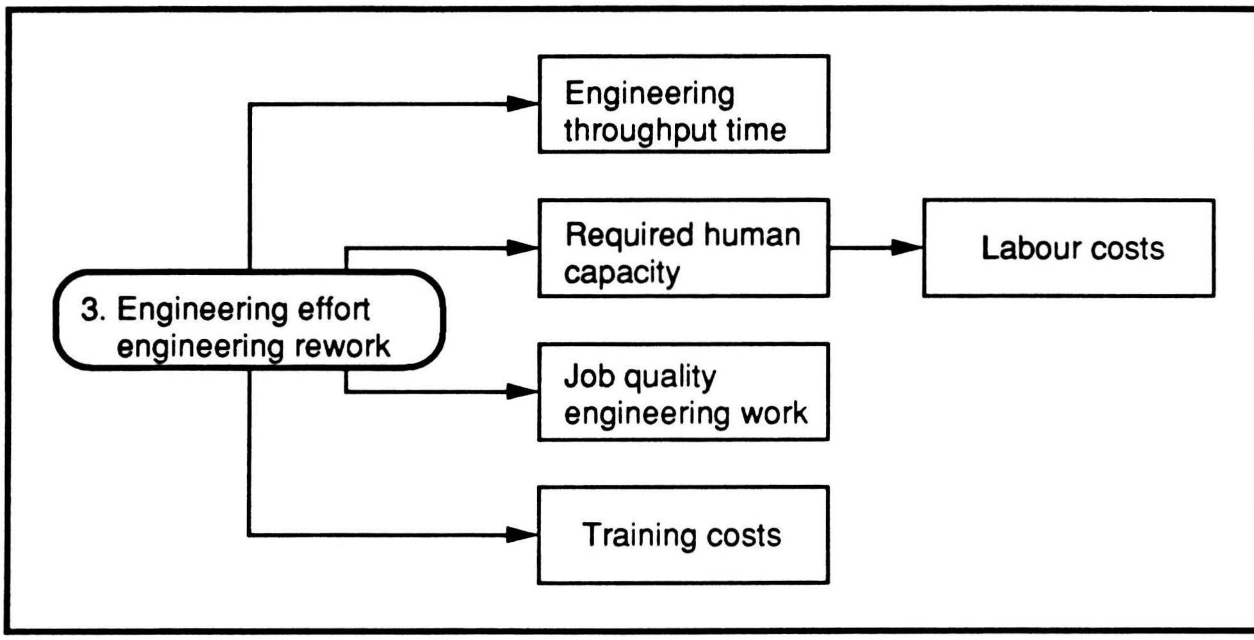

Figure 5: Relations between DC 3 and PI's

Design choice 3: The engineering effort invested in avoiding engineering rework.

This design choice defines the total amount of engineering manhours on average put into one customer order to avoid engineering rework.
Engineering rework is the work which has to be done more than once by the engineers responsible for the design and construction because a developed part is not feasible or because mistakes in the drawings or specifications make production impossible.
Avoiding rework requires communication between engineers and professionals responsible for the work preparation. The engineers know what is required by the customer and which technical standards have to be satisfied by the product. The professionals responsible for the work preparation know the exact possibilities on the production floor. The professionals can also give some useful ideas about the design and construction to make production more efficient and/or more effective.

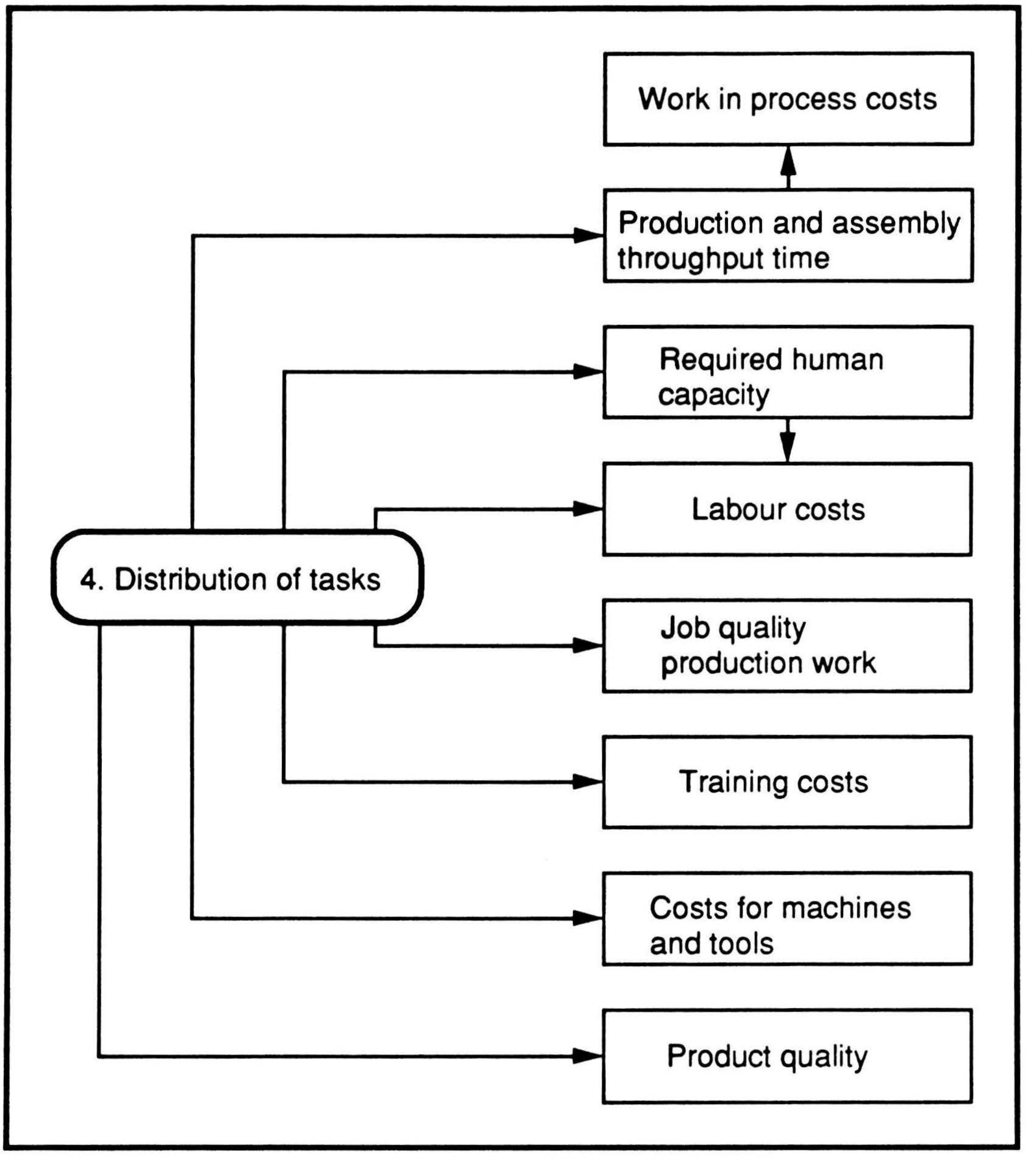

Figure 6: Relations between DC 4 and PI's

Design choice 4: The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization.

This design choice defines the distribution of the five tasks in an organization.
This design choice is tightly connected with a choice for an organizational structure. To distinguish different organizational structures the typology of van Assen, den Hertog and Koopman [4], as described above, is used. According this typology, there are many different organizational structures. To operationalize however this design choice, two extreme opposite organizational structures are used. Many organisational structures exist but the following two structures are chosen to show clearly the consequences of this design choice on the performance indicators. The organizational structures are chosen according the typology of van Assen, Koopman and den Hertog:

Cluster 1:

1. Functional lay-out
2. Centralized and functionally oriented staff
3. Many hierarchical levels and no delegation of tasks

Cluster 2:

1. Group technology lay-out
2. Staff decentralized to groups
3. Few hierarchical levels and many tasks delegated

The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs is completely different in the two organizational structures. Consistent with the kind of organizational structure in the first case is chosen to allocate the five tasks to special staff and services. In the second case is chosen to allocate the five tasks to the operators of the groups. The special staff and services have just a few tasks left and they are decentralized to groups whenever it is possible and reasonable.
For a more detailed description of the contents of the five tasks and of the differences for the contents of the tasks in the two cases is referred to appendix 1.

3.4.2 The performance indicators

The performance indicators used to evaluate the four design choices were chosen after analysis of the literature referred to above. Most of the definitions of the performance indicators are derived from Burbidge [11]. The following performance indicators are related with the four design choices:

1. The engineering throughput time

   Defined as: The time period needed for information to complete the design and construction stages.

   Affected by: DC 1, 2, 3.

   The engineering throughput time will be generally shorter if no or little effort is used for the objectives mentioned under design choices 1, 2 and 3. If more engineering effort is put into communication with customers, suppliers and professionals within the company, the throughput time will generally increase. The variation on the engineering throughput time will be less than in the situation in which no effort is put into communication. This is because the number of "type 2 parts" is roughly proportional to the amount of engineering rework.

2. The manufacturing and assembly throughput time

   Defined as: The time taken to complete a production order, starting at the moment when materials are ready for the first operation, and finishing with the completion of the last operation of the order.

Affected by: DC 4

The throughput time is made up of the following three types of times:

- The transportation time

Defined as: The time taken to transport the materials needed for a production order between the different work centres. The time the order is waiting for transport is included in the calculation of the transportation time.

A group technology organization requires less transportation time for production orders, because the required machines are located close together.

- The waiting time

Defined as: The time spent by production orders waiting to be processed.

In a group technology organization the operators are capable of some detail planning tasks, if the five tasks are allocated to them. Therefore the waiting time can be reduced, because there is more flexibility at the lowest level of the production hierarchy.
In a functional lay-out similar machines are located close together. Thus if a production order enters a work centre the chance of allocating the job to an idle man/machine combination is higher than within a group technology lay-out where a production order is restricted to a particular group.

- The set-up time

Defined as: The time taken to change the tooling set-up on a machine or other work centre.

In a group technology lay-out a family of components or parts are produced in one group. This increases the possibilities for using standard tools and this reduces the total set-up time for a factory.

3. The required human capacity

Defined as: The number of people required to realise the required amount of work they are responsible for within a defined period of time.

Affected by: DC 1, 2, 3.

More engineering (design and construction) manhours used on average for one customer order requires a higher engineering capacity.
The engineering effort used for the communication meant under design choice increases also the required work preparation capacity.

A smaller number of new parts and less rework decreases the required engineering and work preparation capacity.

Affected by: DC 4

The required number of people is dependent upon the required amount of work. The required amount of work for work preparation, detail planning and quality control tasks is probably less if the tasks are delegated to the groups. The mentioned tasks are in that case much simpler because of the clear organizational structure.

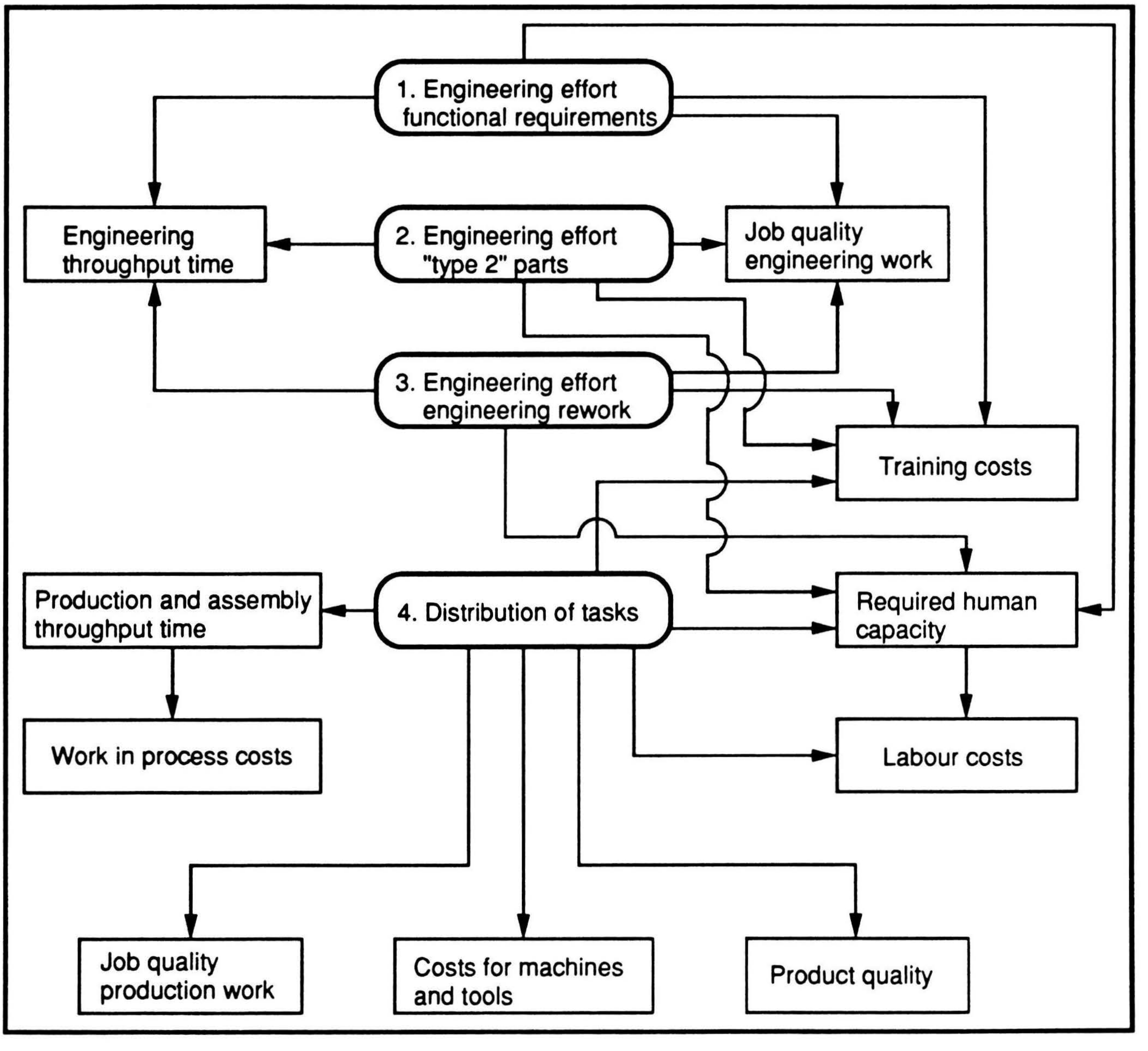

Figure 7: Relations between DC's and PI's

4. Labour costs

Defined as: The required number of people times the wages of these people.

Increased by: PI 3

If it is not permitted to fluctuate the wages of employees, the engineering labour costs are only dependent upon the required engineering capacity.

Affected by: DC 4 and PI 3

The labour costs are dependent upon the required number of people and on the wages of the people. The wages of staff personnel are usually higher than the wages of operators. Less special staff and services are required if tasks for work preparation, detail planning, quality control, maintenance and repairs are delegated to operators. Thus a shift to more operators increases their labour costs but the labour costs for qualified staff decrease. People in industry are paid for the responsibilities they have. When the operators get more responsibilities they should therefore get higher wages.

5. Job quality

Defined as: To have within the job content the opportunity to:

1. Regulate the output of the process, if there are changes in either the input or throughput of the process
2. Introduce changes in the process, to adapt to another environment
3. Achieve the same results in several ways.

Improved by: DC 1, 2, 3.

Job quality of the engineering work:
If the engineers are allowed to use more manhours to communicate with customers, sales representatives, purchasers and the professionals responsible for the work preparation, the three opportunities increase.

Affected by: DC 4

Job quality of the production work:
The job quality is improved by delegating tasks for work preparation, detail planning, quality control, maintenance and repairs to operators. The job quality of the production work is also improved by involvement of operators in personnel policy and product development.

6. The costs of work in process

Defined as: The material costs of the work in process.

Increased by: PI 2

The longer the manufacturing and assembly throughput time, the higher the costs of the work in process.

7. Training costs

   Defined as: The costs needed to train employees in certain capabilities.

   Affected by: DC 1, 2, 3.

   The engineers need to be trained to cooperate and negotiate in an efficient way with customers and suppliers. They also need to communicate in an efficient way with professionals of other disciplines within the company.

   Affected by: DC 4

   If many tasks are delegated to the operators they need training to learn the necessary capabilities. First, they need to learn to operate more than one machine. Second, they have to learn how to do (a part of) the work preparation, detail planning, quality control, maintenance tasks and repairs. Third, they need training in communication and cooperation, because this is required for the new tasks allocated to them.

8. The costs for machines and tools

   Defined as: The costs needed to buy required machines and tools.

   Affected by: DC 4

   Each group in a group technology lay-out should have available the complete set of helping- and setting tools and all machines which they require. A shift from a functional lay-out to a group technology lay-out may necessitate an investment in machines and tools.

9. Product quality

   Defined as: How far the variation in size, weight, shape, finish, and so forth for products or services are maintained within given limits.

   Affected by: DC 4

   When control tasks are delegated to operators in a group technology organization the product control circle is much shorter than in the situation with special quality control people in a functional organization.

3.5. Testing of the model

One of the four tasks described in chapter one was to test the business relevance of the design choices of the Engineering Allocation model and the validity of the relationships between the design choices and performance indicators. Several attempts were made to approach OKP companies in Norway, Germany and the Netherlands. But no company had the resources available or was interested to cooperate with a research project. The only alternative left was to try to have interviews with experienced people to test the model. These interviews resulted not in a validation of the model in the strict sense but more in a gathering of opinions of experts from industry. Several people were selected for these interviews:

1. The marketing and sales manager from SERVI, a company producing hydraulic systems in Trondheim
2. The president of Cox, a company producing winches in Bremen
3. The adjunct head of the engineering department of Fokker, a company producing planes
4. The logistics manager of Stork, a company producing packing machines.

The objectives of the interviews were:

1. Testing if the relationships of the model are present in industry
2. Testing if the relationships between DC's and PI's as distinguished in the model are relevant in industry.

The four people from the different companies were asked to answer the questions listed in appendix 2. They answered the questions from their own experiences in industry.

For three reasons design choice 4 was not selected as a topic of the interviews:

1. The number of references to literature of this subject
2. The quantative kind of relations between the variables distinguished under design choice 4
3. The complexity of the variables and relations compared to the time available in an interview to handle them

The interview material consists of the three first design choices. As it is impossible to handle all the relations distinguished under the three design choices extensively in one interview, the questions are more about the business relevance of the model.
The two main conclusions of the interviews were:

1. Indications were given that the relationships as they are modelled were found to be relevant to engineering work in OKP systems
2. Indications were given that the relationships as they are modelled are present in industry

It was very important that the answers of the interviewed people supported each other. They agreed about the main points of the interviews.

The other conclusions of the four interviews are listed here:

Design choice 1: Defining the functional requirements

1. The customer knows more or less his wishes and demands, but only in functional terms. Negotiation takes place about the wishes and demands of the customer compared to costs, throughput time and quality associated with the product.

2. The engineer is not involved in the negotiating process with the customer.

3. Some wishes and demands of the customer can be changed up until one month before the assembly starts.

4. The experience of the engineer responsible for the design fixes the number of standard solutions used in a product. The sales representative is not capable of having a contribution in this process.

5. Sometimes there is cooperation between the professionals responsible for the work preparation and the engineers responsible for the product development. But this is an exception. Even more an exception is cooperation with the management of the production or assembly department during the product development.

Design choices 2 and 3: "Type 2" parts and engineering rework

6. It occurs sometimes in practice that the design or construction of a new part appears to be not feasible for production and assembly. When this occurs, it is first tried to solve the problems on the production floor or during the assembly, but sometimes it may have to go back to the engineering department in order to solve the problem.

7. The main differences between standard parts and new parts are in the work preparation. For standard parts special tools are developed to manufacture them but new parts may not justify an investment in such tools.

8. Standard solutions are used as much as possible. The choice for standard solutions is however for the greater part restricted by the customer specifications.

9. The professionals responsible for work preparation identify most of the errors which may cause problems to engineers responsible for design and construction. The drawings and specifications are returned to the engineering department to correct them.

CHAPTER 4: THE IMPLEMENTATION OF THE MODEL

4.1 Introduction

This chapter discusses the implementation of the Engineering Allocation model on the FOF demonstrator. The FOF demonstrator contains the theories and models developed within FOF in the form of a computer tool. Originally it was planned to implement the FOF models on a designer's workbench, but there were not enough resources and time available to realise this objective. The demonstrator is a software tool which can demonstrate the models developed within FOF by means of one common case (particular model).
Different computer tools are used to implement the Engineering Allocation model on the FOF demonstrator. The simulation package STELLA [16] is used to implement the main part of the model. STELLA is a simulation package which has been used in the development of several FOF drawing models. To model some specific parts of the Engineering Allocation model the simulation program SIMMEK [6] is used. SIMMEK is a computer based discrete event simulation tool for performing analysis on manufacturing systems. Some results from the simulation in SIMMEK are used as input to the STELLA model.
In the first section of this chapter the implementation making use of the simulation program SIMMEK is presented. The implementation making use of the simulation package STELLA is described in the second section. In the last section of this chapter the results of the attempts to develop interfaces with other models are described.

4.2 The SIMMEK implementation

SIMMEK is a computer based discrete event simulation tool for performing analysis on manufacturing systems [6]. It was developed at the production engineering department of the SINTEF institute in Trondheim. In this section a general description of the model in SIMMEK is given. For more detailed information is referred to appendix 3.

For two reasons the simulation tool SIMMEK is used to implement some specific parts of the Engineering Allocation model.
First, it is very easy to model manufacturing departments on a very high level of detail within SIMMEK. This makes it possible to transform a functional lay-out into a group technology lay-out, thus it makes it possible to model design choice 4 on a detailed level.
Second, the Order Release model, the other model within the workflow view, uses the same simulation tool. This facilitates a possible interface between both models (Section 4.4).

For all eleven drawing models a common case was chosen for implementation on the FOF demonstrator, hence all models run on the same data. This case is called "The Eurowinch case". Data are derived from a winch company in Bremen.

Within the Engineering Allocation model, two models have been built within SIMMEK. The two models represent two different situations as described under design choice 4 (Section 3.4.1).

Design choice 4 is:

The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization.

For reasons of time and complexity the tasks for detail planning and maintenance and repairs are not implemented in SIMMEK. The tasks implemented in SIMMEK are the tasks for work preparation and quality control. Transportation between work centres and departments and tasks for execution are also considered in the implementation. Only the production and the assembly department are modelled.

Two extreme situations are modelled as extreme cases of design choice 4:

Cluster 1:

1. Functional lay-out
2. Centralized and functional oriented staff
3. Many hierarchical levels and no delegation of tasks

Cluster 2:

1. Group technology lay-out
2. Staff decentralized to groups
3. Few hierarchical levels and many tasks delegated

Within cluster 1, the production and assembly department are organized along a functional lay-out. The tasks for work preparation, detail planning and transportation are allocated to special staff and services.

Within cluster 2, the production and assembly department are organized along a group technology lay-out. The tasks for work preparation, detail planning and transportation are allocated to the members of the groups.

To make the transition to a group technology lay-out from the original functional lay-out, the theories and methods of the production flow analysis from Burbidge [12] are followed.

The following results from the simulation runs of both SIMMEK models, each representing one situation as described above, are used as input to the STELLA model:

1. The manufacturing and assembly throughput time
2. The required human capacity
3. The costs for machines and tools.

For a more detailed description of the SIMMEK implementation is referred to appendix 3.

4.3 The STELLA implementation

STELLA is a simulation package which has been used in the development of some of the FOF drawing models. STELLA has been chosen to implement the Engineering Allocation model on the FOF demonstrator for the following reasons:

1. An initial study done for FOF by Breuls [7] shows that STELLA is appropriate for the kind of relations which are contained in the Engineering Allocation model
2. Four other models within the FOF-project use STELLA for their implementation on the FOF demonstrator. This increases the possibilities for an interface with these models.
3. STELLA is a very user-friendly tool. As the author of this report is not a programmer and did not have the time available to become one, this is an important argument to use STELLA.

STELLA is used to implement the entire Engineering Allocation model and to use data derived from the SIMMEK models as input. The SIMMEK models and the STELLA model are not directly connected. Some results of the SIMMEK model are used as input data for the STELLA model. This happens not automatically but by hand. In this section the implementation of STELLA is presented according to the SADT methodology [17] (Appendix 4).

In the model three departments are distinguished, each representing a particular phase in a product's cycle (development, manufacturing and assembly):

1. Design and construction
2. Work preparation and planning
3. Production and assembly

Production and assembly are joined together within STELLA because they are both analyzed on a more detailed level in the SIMMEK models. The first department is used for the implementation of design choices 1, 2, 3. For implementing design choice four of the model, two extra departments are created:

- Work preparation and planning
- Production and assembly

The reason is that by changing the value of design choice 4, different input data are derived from the SIMMEK models for the throughput time and work in process of the production and assembly department. Creating two extra departments in STELLA facilitates the use of the input data from the SIMMEK models.

Input to the STELLA model are customer orders expressed in terms of:

1. Number of customer changes (after the functional requirements have been fixed)
2. Number of new parts
3. Amount of engineering rework

Customer orders require work from each department. The amount of required work is dependent on the values of the three variables.

Design choice 1, the engineering effort invested in defining the functional requirements, can be set on a scale between 0 and 100%. By choosing 100% on the scale, a maximum of engineering manhours is invested in defining the functional requirements for the customer order. By investing the maximum of engineering manhours the need for changes by the customer on the product specifications after the functional requirements have been fixed is reduced to zero. The exact amount of engineering manhours required for reducing the possibility of changes to zero can be different for each customer order. This is dependent on the complexity of the demands and wishes of the customer. When the value of 0% on the scale is chosen no engineering manhours are invested in defining the functional requirements.

Design choice 2, the engineering effort invested in reducing the number of new parts of "type 2", can also be set on a scale between 0 and 100 %. By choosing 100% on the scale, a maximum of engineering manhours is invested in reducing the "type 2 parts". By investing the maximum of engineering manhours the number of "type 2 parts" is reduced to zero. The exact amount of engineering manhours required for reducing the number of "type 2 parts" can be different for each customer order. This is dependent on the initial number of "type 2 parts" of the specific customer order. When the value 0% on the scale is chosen no engineering effort is invested in reducing the number of new parts of "type 2".

Design choice 3, the engineering effort invested in avoiding engineering rework, can also be set on a scale between 0 and 100 %. By choosing 100% on the scale, a maximum of engineering manhours is invested in avoiding engineering rework. By investing the maximum of engineering manhours all the amount of engineering rework is avoided. The exact amount of engineering manhours required for avoiding all the engineering rework can be different for each customer order. This is dependent on the initial amount of engineering rework of the specific customer order. When the value 0% on the scale is chosen engineering effort is invested in avoiding engineering rework.

Design choice 4 concerns the distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization. When setting the design choice tasks can be distributed to either "operators" or "special staff and services". Related with this design choice is the choice for a functional or group technology lay-out as described in section 4.2 and appendix 1.

The calculation of the performance indicators is also done within STELLA. Please refer to appendix 5 for a more detailed description and to the model documentation [5].

The engineering throughput time is not implemented because of two reasons.

1. It is not possible within STELLA to measure the effect of the variation of the engineering throughput time on the individual customer orders. This is because it is not possible within STELLA to send a specific customer order back from the work preparation and planning department to the design and construction department.

2. Within the STELLA model the required capacity increases if more work arrives for a particular department. The throughput time is therefore supposed to be within fixed limits.

The manufacturing and assembly throughput time is also kept within limits. But this performance indicator is related with design choice 4, and therefore two different production and assembly departments are modelled. The limits for the throughput time of each department are dependent upon the results of the simulations in SIMMEK and hence the performance indicators range between these limits.

The required human capacity of the different departments is dependent on the input of required manhours as specified by the customer orders and also influenced by the four design choices. Within the model the capability to adjust the capacity after a period of four weeks is also available.

The labour costs are directly dependent upon the required human capacity and upon then distribution of tasks. The wages of the operators are increased if the tasks for work preparation, detail planning, quality control and maintenance and repairs are allocated to the operators.

The job quality of the engineering work is directly dependent on the number of engineering manhours used for cooperation with customers, suppliers and other professionals within the company.
The job quality of the production work is only dependent on design choice four. The job quality is very high if the tasks for work preparation, detail planning, quality control and maintenance and repairs are allocated to the operators. If these tasks are allocated to special staff and services the job quality of the production work is very low.

The costs of the work in process are calculated from the amount of work in process in the production and assembly department. Dependent on the allocation of tasks, one of the two production and assembly departments is used to model the work in process costs.

The training costs are based on a yearly training need for new people and on the values for the four design choices. The higher the values for the three first design choices, the higher the training costs. The training costs are also influenced by the fourth design choice. The setting of design choice 4 to "operators" results in higher training costs than setting design choice 4 to "special staff and services".

The costs for machines and tools are derived from the SIMMEK models. The costs for machines and tools are higher if design choice 4 is set to "operators" than if this design choice is set to "special staff and services" (Appendix 1).

The product quality is directly dependent on design choice 4. The average costs for production rework are lower if design choice 4 has the value "operators" than if this design choice has the value "special staff and services".

4.4 The interfaces

This section discusses the interfaces between the Engineering Allocation model and the other models within FOF.
As described in task 2 (Chapter 1) most attention should be given to an interface with the Order Release model. The Order Release model was also developed at the SINTEF institute in Trondheim and it is the only other model currently belonging to the workflow view.
The attempts to establish an interface were however restricted by the state of the models and the limited time available. The development of the Engineering Allocation model started in February 1991. The FOF project asked for an entity relation diagram of the model on the 15th of February 1991. In the case of the Engineering Allocation model it was not possible to tell if the entity relation diagram of 15 February would be the final version.
The entity relation diagram should have been the basic tool for developing an interface with the Order Release model.
After the engineering Allocation model reached its final stages of development the possibilities for an interface with the Order Release model were reconsidered. SIMMEK, the simulation tool used by the Order Release model appeared to be appropriate to model some parts of the Engineering Allocation model (Section 4.2). It was agreed upon the use of the same SIMMEK models for the FOF demonstrator. Some results from the simulation runs of these models are used in the STELLA implementation of the Engineering Allocation model (Section 4.2). Because of the limited time available it was not possible to integrate the SIMMEK models with the STELLA model so that input for STELLA was derived automatically from the SIMMEK models.

An interface between all the models is the common user interface of the FOF demonstrator. All the models have the same entry screens and they use the same template for presenting the design choices and performance indicators.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This chapter discusses the conclusions of the master project and recommendations for the further development of the Engineering Allocation model within the FOF II project.

1. The relationships distinguished in the Engineering Allocation model have not been empirically tested. Section 3.5 describes the relationships which are distinguished in the model and which are considered to be relevant and present in industry. Some experts were asked to give their opinion about the relevance of the relationships of the model (Appendix 2).
   This is an indication for the validity of the relationships. It is very important to investigate the validity of the model empirically before the model is developed any further.
   Some important relationships of the model need empirical support:

   - The relation between the engineering effort invested in defining the functional requirements and the number of changes by the customer on the product specifications after the functional requirements are fixed
   - The distinction between standard parts and new parts.
     How do companies treat this distinction?
   - The distinction between "type 1 parts" and "type 2 parts".
     How do treat companies this distinction?
   - The assumption that engineering rework always is discovered during the work preparation. Is not some engineering rework discovered during manufacturing?

2. Communication is considered to be very important in the Engineering Allocation model. All four design choices handle communication in one way or another. In the model, however, it is only stated who communicates with whom. It is not stated how this communication should be structured. Should the engineers be members of multi-disciplinary project teams, each team responsible for the development, manufacturing, assembly and delivery of a particular product? How should the customers and suppliers communicate with these project-teams? How is simultaneous and concurrent engineering related with this? Are there any other effective communication structures?
   These questions need to be answered in a further development of the model in a FOF II project.

3. For the Engineering Allocation model only one case is implemented on the FOF demonstrator. This case, the Eurowinch case, is a common case used by all eleven FOF models, hence all models run on the same data. This implemented model is a so called "particular drawing model" (Chapter 2). It is not easy to apply the model to another case. The data of the Eurowinch case are integrated within the relationships as they are defined within the STELLA implementation. In further development work with the Engineering Allocation model, if is chosen to apply the model for more cases, it would be useful to reconsider the use of STELLA. Within another software tool it may be easier to implement a so-called "reference drawing model" (Chapter 2) and apply this model to several cases. The use of a database is within STELLA not

as easy as within other tools, for example Hypercard.

4. The Engineering Allocation model is not concerned with exact tasks of the engineers. A detailed description of the engineering tasks can be very interesting from different points of view and these are outlined here.
   First, the number of engineering manhours required for communication can be compared to the number of engineering manhours required for other tasks.
   Second, a detailed description of the engineering tasks can result in an interface between the Group Design model [8] and the Engineering Allocation model. The Group Design model is concerned with the grouping of people in the most efficient way. In the current state the model is only applied for the manufacturing and assembly department. If the engineering tasks are described in detail it might be possible to apply the Group Design model for the engineering department. Changes in the setting of the first three design choices of the Engineering Allocation model will have consequences for the performance indicators distinguished in the Group Design model.

5. Group technology is in the Engineering Allocation model only applied to the manufacturing and assembly departments. Burbidge [9] states that group technology also can be applied to departments other than the manufacturing and assembly departments, for example an engineering department or staff departments. In a further development of the Engineering Allocation model it could be very interesting to investigate the possibilities of applying group technology on the engineering department.

ABBREVIATIONS

CIM	Computer Integrated Manufacturing
DC	Design Choice
DCPI	Design Choices - Performance Indicators network
ESPRIT	European Scientific Program for research and development in Information Technology
FOF	Factory Of the Future
IFIP	International Federation of Information Processing
IV	Intermediate Variable
OKP	One of a Kind Production
PI	Performance Indicator
TUE	Eindhoven University of Technology

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APPENDICES

APPENDIX 1: DESIGN CHOICE 4

Design Choice 4: The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs

INTRODUCTION

This design choice describes how tasks for work preparation, detail planning, quality control, maintenance and repairs can be distributed in an organization.
The responsibility for each task can be distributed to either special staff and services or to operators. To a large extent the degree of distribution determines the job content and the job quality of the production work. It is also connected with the choice for an organizational structure. These relations are explained later in this section.

The following tasks are distinguished and a general description of the contents is given:

Work preparation tasks

- Work instructions and detailed drawings
  If necessary making new work instructions for new parts.
  If necessary preparing the drawings which come from the engineering department for the operators.

- Routing
  Fix the routing of the production orders through the production department.

Detail planning tasks

- Prioritizing and scheduling
  Give the different production orders priorities and schedule them. This prioritizing and scheduling of the orders takes place at different levels and with different time-scales. The operators are only capable of planning orders after they are released to the shop floor. Only this level is considered and the planning of production orders at a higher level is ignored.

- Planning of drawings, work instructions and helping-tools
  Take care that the needed drawings, work instructions and tools together with the production order arrive at the right work centre and at the right time.

- Allocation of operators to machines
  Allocate the operators to the different machines if there are no fixed man-machine combinations.

- Distribution of work in a work centre
  Distribute the production orders over the man-machine combinations.

Execution tasks

- Execution
  Execute the production orders; turning, milling, drilling, gear cutting etc. This includes programming the machine and placing the needed tools on the machines.

Quality control tasks

- Quality control
  Control whether the products or parts fulfil the required quality specifications. These quality specifications consider the variation in size, weight, shape, finish and so forth of the parts.

Maintenance tasks and repairs

- Maintenance and repairs
  Maintain machines and tools to prevent disturbances. Repair the machines or tools if they break down.

In each organization these tasks are distributed differently and the tasks themselves vary. It is possible to delegate (a part of) the five tasks to operators. For other tasks like hiring new personnel, identifying the need for training and education and developing new products, special departments are usually responsible. It is however possible to involve production people also in these tasks. This improves the job quality of the production work.

As mentioned earlier, this design choice is tightly connected with the choice for an organizational structure. The typology, described by van Assen, den Hertog and Koopman [4] is used to distinguish different organizational structures. Within the typology the following three dimensions are used:

1. A process-oriented versus a product-oriented lay-out of all operations on each aggregation level (task, group, department, plant, entire organization)
2. The extent to which help-services and staff-services are integrated with each other and with the production department. Four degrees of integration are distinguished:
   - a centralized and functional-oriented staff
   - horizontal relations between the staff-services
   - operational staff-groups
   - staff decentralized to product-groups
3. The number of hierarchical levels and the extent of delegation of tasks.

The combination of positions on each dimension defines for the larger part the communication structure, the decisional structure and the task structure of an organization. These three structures define the opportunities to improve the job quality of the individual workers.

Two consistent clusters of extremes on the three dimensions are connected with two opposing methods of distributing the distinguished tasks.

The first cluster contains:

1. A process-oriented or functional lay-out
2. A centralized and functional-oriented staff
3. Many hierarchical levels and no delegation of tasks

In this kind of organization the five tasks are all allocated to special staff and services.

The second cluster contains:

1. A group technology lay-out
2. A staff decentralized to groups
3. Few hierarchical levels and many tasks delegated

This organizational structure is in accordance with the principles of the sociotechnical view, described by van Amelsvoort and Kuipers [3]. The tasks are all delegated to operators in an autonomous group. The job quality of the production work is considered very important.

These two combinations are chosen because they form two clear consistent and opposing clusters at methods for distributing tasks. Combinations other than these two are of course possible. Not all of them however are consistent clusters.

For example:

1. A functional lay-out
2. A decentralized staff
3. Few hierarchical levels and many tasks delegated to operators

is not an efficient combination, if not, an impossible one. The operators lack the overview to estimate the consequences of changes in their work for the next work centre. Thus they are not capable of doing all the tasks they get distributed.
After one position on the three dimensions is fixed, the other two are limited to a certain range to get a consistent cluster.

The two clusters are pure examples of the two extremes on the three dimensions. It is unlikely that a factory in real-life exactly fits into either of the clusters, but this division is made for the purposes of illustration of the ideas behind the Engineering Allocation model.

THE FIRST CLUSTER

The tasks for work preparation, detail planning, quality control, maintenance and repairs allocated to special staff and services

The distribution of the distinguished tasks to *special staff and services* is consistent with the first cluster of choices:

1. A functional lay-out
2. A centralized and functional-oriented staff
3. Many hierarchical levels and no delegation of tasks

The functional structure of the production department is based on process specialization. The workers in the factory are divided into work centres, each of which specializes in a particular process or part of a process. The work centres have a number of universal machines and are specialized in such processes as turning, milling, drilling, grinding and gear cutting. Often there is a fixed man-machine combination and the foreman of each work centre is a specialist.

The contents of the tasks within this kind of organizational structure are described in the following section.

Work preparation tasks

- Work instructions and detailed drawings
  The engineers make the work instructions during the work preparation phase. These engineers need an overview, because many operations and processes are required to manufacture a product. They also need knowledge of the different processes to make proper work instructions. A special department makes the detailed drawings.
  The operators of the different work centres are not capable of estimating the consequences of small deviations in their work on the quality of the final product. Therefore detailed drawings and extensive work instructions are necessary. These instructions insure that the operators know exactly what to do, and if followed closely this will lead to good quality, assuming the detailed drawings and extensive work instructions were correct. It is difficult to check whether the drawings and instructions are correct because nobody at the operator level has a complete overview of the entire process.

- Routing
  Special staff makes the routings for the production orders. To make optimal routings for a functional organized production department is a complex task. Among the things the planner should consider are the set-up time, transportation time and queuing time of the system. Knowledge of the different functions and an overview of all the processes is essential. The routing is complex because a production order is divided into many different operations. For each operation the order has to go to another work centre in order to be completed. The experts making the routing define the sequence in which the production order visits the work centres. Alternative routings are sometimes possible, for example drilling and milling may be done in

reverse order. The expert, however, assumes a fixed sequence, and nobody at the production floor is concerned if this is the optimal routing under the given, and always changing, conditions or not.

Detail planning tasks

- Prioritizing and scheduling
  Because of the complicated nature of this task, it requires the ability of an expert. He needs a complete view of the different work centres to make a sensible and realistic plan.

- Planning of drawings, work instructions and helping-tools
  The planning of the drawings, work instructions and required tools follows the fixing of the complex routings of the production orders. Only someone with an overall view of the routings of the production orders is capable of doing this task.

- Allocation of operators to machines
  In most cases there are fixed man-machine combinations, therefore allocation is done once and is fixed for a period of time.

- Distribution of the work in a work centre
  The foreman gets the production orders from the planning department and allocates the work to the different man-machine combinations. He tries to consider set-up times and specializations within the work centre, as to maximize the productivity.

Execution tasks

- Execution
  Fixed man-machine combinations, fixed routings, extensive work instructions and detailed drawings all made by staff personnel limit the operators extremely. Operators are only allowed to program their machines, place the needed helping-tools and execute the production orders in a fixed sequence.

Quality control tasks

- Quality control
  Quality personnel controls the quality of the product. They are capable of estimating the consequences of a small deviation in shape or size on the final quality of the product. They have knowledge about the different processes and know the minimum requirements with respect to the functionality and quality of the product.

Maintenance tasks and repairs

- Maintenance and repairs
  The maintenance and inspection of the machines and tools is done by a special department. Repairs of machines in the case of break down is done also by a special department. The operator gives a message to the maintenance and repair department and they come to fix it at their leisure.

A functional lay-out with a centralized staff, many hierarchical levels and no delegation of tasks results in a rigid organization. Special planners, engineers, quality people and mechanics are needed to make routings, extensive work instructions, detailed drawings, to do quality controls, maintenance and repairs. The operators lack the overview and therefore almost everything has to be fixed before the production starts. They are not able to estimate the consequences of slight changes in drawings, work instructions or routings, for the product quality or throughput time. The communication is largely done through documents.

In summary, the functional organization limits extremely the choices on the other two dimensions. People are needed with an overall view, thus a centralized staff, with or without horizontal relations, and almost no opportunity to delegate tasks is a logic result. If for example quality control tasks are delegated to the operators, they should get very extensive instructions which specify all possible mistakes or errors, the consequences of such errors and the corrective actions for these mistakes. In this kind of situation it is easier to have special staff which does not need these extensive instructions.

A functional structure with the distinguished tasks distributed as described before, has in general the following advantages and disadvantages:

Advantages:

- At the time of the work preparation there is a possibility of flexible adjustment to several machines. Often, more than one machine can do the required work for a particular production order
- The process knowledge is high, operators of the same work centre are able to teach each other the entire process of the work centre
- The range of different products which can be produced is high, because the operators are specialists
- The machines which require the same special provisions, like a certain climate or isolation can be placed together

Disadvantages:

- The planning of the production orders is complex
- It is difficult to trace the progress of a particular production order in larger organizations
- It is difficult to estimate the consequences of a small deviation in one process-step, because the overview on the product is absent. This makes quality control difficult.
- It is difficult to control the throughput time of the individual production orders because of the complex routings
- The average throughput time of the production orders is long, because of the long transport and queuing time.
- The average work in process is high to realize a high utilization rate for the machines
- The work instructions are so detailed that they limit the choice for a machine in one work centre and this causes unnecessary queuing time

THE SECOND CLUSTER

The tasks for work preparation, detail planning, quality control, maintenance and repairs allocated to operators

The distribution of the distinguished tasks to *operators* is consistent with the second cluster of choices:

1. A group technology lay-out
2. A staff decentralized to groups
3. Few hierarchical levels and many tasks delegated

Group technology, according to Burbidge [9], is an approach to the work-organization in which the production units are relatively independent groups. Each group is responsible for the production of a given family of parts or products. The smallest organizational unit is the group, but the same principle of organization is used when forming larger organizational units such as departments.

A group [9] is a combination of a set of workers and a set of machines or other facilities laid out in a reserved area, which is designed to complete a specified set of parts or products.

A family is the set of parts or products produced by a group.

The other three characteristics, staff decentralized, few hierarchical levels and many tasks delegated, follow current sociotechnical principles [3]. The sociotechnical view, like the group technology, advocates groups as the basic organizational units.

A group is defined in the following way:

A fixed group of multi-skilled people who are responsible for execution, control, evaluation, analysis and improvement of a complete production task and having sufficient resources for this task.

A family of parts or products, defined by the group technology theory, is a good example of a complete production task. The group technology however is basically concerned about an organization based on families of parts or products giving easier planning, and a simpler production control system than in a functional organization. This leads to reductions in throughput time, work in process and stocks. The sociotechnical principles however go beyond this and advocate more responsibilities for the group members. Many tasks which otherwise are distributed to the staff personnel are now allocated to the operators. Delegation of tasks for work preparation, detail planning, quality control, maintenance and repairs to a team of workers coupled with involvement in personnel policy and product development improves their job quality and is the key to successful groups.

The next step is to allocate the tasks to each individual. Here only some examples are given of this step, because this depends on the individual needs of the employees. Some operators want less or no responsibilities while others have their own special preferences. The main objective should be that the tasks are allocated to the operators in a way that fits their needs. These tasks should, of course, contain enough responsibilities for a high job quality.

The contents of the tasks within this kind of organizational structure are described in the following section.

Work preparation tasks

- Work instructions and detailed drawings
  The operators are multi-skilled, able to program the machines and used to cooperating with the other members of the group. Together they have a complete overview of the required operations and together as a group they are capable of executing all these operations. Extensive work instructions and detailed drawings are not necessary in this kind of organization. The operators need to know the critical specifications of the product or parts to satisfy the quality demands. For this purpose general work instructions and sketches from the engineers are sufficient. They are capable of translating the specifications into programs for their machines. The communication is done by critical specifications, sketches and most importantly cooperation between the operators; instead of solely through documents as in the functional organization.

- Routing
  The routing of the production orders should only identify the restrictive relations between operations. These relations show which operations have to succeed each other. In most cases the sequence is a matter of choice. The multi-skilled operators should decide upon the sequence of the operations while they are working. Depending on the availability of machines, the helping-tools which are set up, the due dates of the orders and the required operations, they should determine the sequence of the operations.
  It is probably most efficient that one member of the group identifies the restrictive relations. This job can of course rotate between several operators. This man should cooperate with the engineers to minimize the restrictive relations during the technical specifications phase.

Detail planning tasks

- Prioritizing and scheduling
  One planner can be delegated to the group. He plans the production orders at an aggregated level and communicates with the sales representatives about reliable delivery dates. In this way, it is possible to have reliable and short delivery times. If possible, the planner clusters similar production orders, which require the same helping-tools. He tries to release these orders together.
  The operators decide in which sequence the production orders are executed after they have been released. Their decision is dependent upon the set-up times for the required operations and upon the due dates of the production orders. The operator has a complete overview and, if necessary, they cooperate with the others to optimize the

scheduling.

- Planning of drawings, work instructions and helping-tools
  Each group has its own place to store drawings, work instructions and helping tools. In the ideal situation they do not share any helping-tools with other groups. The operators themselves get the instructions, drawings and tools and bring them either to the next machine or back to the store.

- Allocation of operators to machines
  In most cases there are no fixed man-machine combinations. Most operators are multi-skilled and are able to work with more than just one machine. It is however possible that a particular machine requires such skills that only one person is capable of operating this machine. It is also possible that someone only wants to work on one particular machine. These are two examples of fixed man-machine combinations. The allocation of the other operators is dependent upon their own desires and upon the characteristics of the production orders. The members of the group can agree on who will operate each machine. Of course they should maintain their skills by operating more machines in the group.

- Distribution of the work in the group
  The members of the group decide together how to distribute the production orders to the operators. They should do this frequently, once a day, to compensate for leave, absence or rush orders.

Execution tasks

- Execution
  The execution tasks do not really differ from the execution tasks described under the functional organization. The only difference is that the operators are multi-skilled and thus they can work simultaneously with more machines of different nature if the mechanistic allows for this.

Quality control tasks

- Quality control
  The operators have a complete view and are able to estimate the consequences of small deviations for the final quality. They "understand" the quality demands, because they know all the processes. Because of this the quality demands do not need to be very extensive. The operators do not need an extensive description of each possible deviation or mistake together with the consequences for the final product quality. It is sufficient to explain the required functionality and the operator is then capable of controlling this.

Maintenance tasks and repairs

- Maintenance and repairs
  Each group can have one mechanic who is capable of repairing all the machines of the group. However, preventive maintenance and small repairs can be done by the

operators themselves.
The mechanic who is allocated to a group should also be capable of doing some production work. If there are no repairs, it is possible to use his capacity in the production process. It also increases the understanding for each others work, the mechanic understands the work of the operator and this has positive consequences for his own work.

Within this kind of organization, it is clear that the operators get much more responsibility. They get a "complete job", not only execution tasks but also work preparation, planning, maintenance and repair tasks (job enrichment). The members of the group are also multi-skilled and capable of operating more than one machine (job enlargement). The opportunities to involve the workers in, for example, the product development process and hiring new personnel are obvious. This is also advocated by the sociotechnical view.
In a functional organization the communication was for the greater part done by documents. In a product-oriented organization, as described above, the people communicate through cooperation.
A product-oriented organization can also be combined with other choices on the two remaining dimensions. This kind of organization does not limit the other choices as much as a functional organization does.

A group technology structure combined with a decentralized staff and many tasks delegated will in general have the following advantages and disadvantages:

Advantages:

- The planning is simpler because the detail planning can be done within the group itself
- The throughput time is shorter than with a functional lay-out because there is less transportation time
- The set-up time will reduce because a family of parts has more or less the same characteristics
- The group can be responsible for the quality of the family of parts they produce
- It is possible to involve the operators in other tasks
- Indirect costs for planning and coordination will decrease
- Operators become more flexible and can operate more than one machine within the group

Disadvantages:

- Less flexibility at the time of the work preparation because the groups are limited to a certain range of parts
- Problems can occur when allocating new parts to a certain group
- Special training is needed to keep the skills of the operators on a high level, because they do not learn their specializations on the job
- More machines are required for each group to produce the entire family of parts
- Competition can start between groups disturbing the communication between them
- It is not possible to place machines which need a special environment, for example safety restrictions, in the same area as the other machines of the group

APPENDIX 2: QUESTIONS LIST

Questions about the process of defining the functional requirements

1. Does the customer exactly know his demands and wishes or are these determined during a process of cooperation and negotiating?

2. What is the influence of the engineer on the choice made by the customer? (Is it for example possible that a customer is convinced by an engineer to take a standard part instead of a new part?)

3. Up until what point in the negotiation process has the customer the ability to choose alternatives?

4. How are "old" solutions re-used for new customer-orders? Is this dependent on the experience of the designer, the engineer, or the sales representative or is all information documented so that other people can refer to it during the negotiation process?

5. What organizational levels cooperate with each other during the process of defining functional requirements? (Are for example the professionals responsible for the work preparation involved, or professionals from the manufacturing or assembly department?)

6. Does it occur that customers have changes in their specifications after design, construction or even after production or assembly has been started?

7. How often are these changes caused by miscommunication between customer and representatives of the company during the process of defining the functional requirements for the product?

8. Does it occur that some corrections have to be made after delivery of the product to adjust the product to the environment in which it has been manufactured to function in?

Questions about new parts and engineering rework

9. What are the average differences between standard parts and new parts in terms of:
   - costs
   - throughput time (for design, construction, work preparation, production and assembly)
   - quality

10. Does it occur that a particular design or construction of a new part is not feasible for production and assembly?
    (How often does this occur? What are the consequences? Does the production order go back to the work preparation or even the construction and design, or do the production or assembly people solve these problem themselves?

11. How accurate and reliable are the estimations for costs, quality and throughput time for new parts? (At the time of the tender and at the time of the work preparation)

12. Are the new parts which probably will be used for only one order distinguished from new parts which also will be used for other future orders? (Is there a different procedure or strategy for these two kind of new parts? What are the differences in strategies?)

13. To what extent are standard solutions used for new customer orders? (Does a certain strategy exist to use as much standard solutions as possible?)

14. At what level of detail are the design, construction, planning and the division between standard and new parts fixed when the tender is set?

15. When are the professionals responsible for the work preparation involved in the product development? (Is there any cooperation with people from the production or assembly department?)

16. Does it occur that the professionals responsible for the work preparation qualify a particular design or construction as not feasible? (How often does this occur? Do they send it back to the engineering department or do they solve the problem themselves? How is this engineering rework identified? Is there a kind of checklist available or is this all done by experience?)

17. How much freedom is available to the engineers responsible for the design and the construction in making decisions?

18. How much freedom do the professionals responsible for the work preparation have in making decisions? (Are they for example allowed to change things in the construction to make the design or construction more appropriate for the production or assembly?)

APPENDIX 3: THE SIMMEK IMPLEMENTATION

INTRODUCTION

The purpose is to evaluate design choice 4 of the Engineering Allocation model. This design choice is:

> The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization.

This design choice is tightly connected with the choice for a particular organizational structure. To distinguish different organizational structures the typology of van Assen, Koopman and den Hertog is used [4]. To operationalize this design choice two extreme opposite organizational structures are chosen. These two are chosen to show clearly the consequences of the design choice on the performance indicators. The first organizational structure is:

Cluster 1:

1. A functional lay-out
2. A centralized and functional-oriented staff
3. Many hierarchical levels and no delegation of tasks

For the implemented model in SIMMEK [6], it means that the manufacturing department is organized along a functional lay-out. The tasks for work preparation and quality control are allocated to special staff and services. (For reasons of time and complexity the distribution of tasks for detail planning, maintenance and repairs is not implemented.)

The second organizational structure is:

Cluster 2:

1. A group technology lay-out
2. A staff decentralized to groups
3. Few hierarchical levels and many tasks delegated

For the implemented model it means that the manufacturing department is organized along a group technology lay-out. Specialists are delegated to the groups and the tasks for work preparation and quality control are delegated to the members of the group.

The following performance indicators are used to evaluate design choice 4 using SIMMEK:

1. Manufacturing and assembly throughput time
2. Required human capacity
3. Required machines and tools

"THE EUROWINCH CASE":

For all the eleven drawing models one common case is chosen for implementation on the FOF demonstrator. This case is called "The Eurowinch case". Data is derived from a winch company in Bremen. Not all the required data was available, so assumptions about data are made and some data is fabricated. The situation for the winch company in Bremen at this moment is that the company has a functional lay-out, a centralized and specialized staff and no delegation of tasks. This situation is comparable to the first organizational structure described above. By the user of the model this organizational structure can be changed into a group technology lay-out, with tasks being delegated to members of the group.
Customer order data are common to both situations.

The product:

The company Eurowinch makes three different kinds of winches:

Hydraulic winch	:	30 a year
Electric winch	:	15 a year
Steam winch	:	5 a year

The winch consists of ten parts, all these parts can be customized (OKP):

1. Hydraulic system
2. Pedestal bearing
3. Warping head
4. Drum shaft
5. Clutch at casing
6. Clutch at pedestal bearing
7. Band brake
8. Pinion for planetary gear
9. Rope drum
10. Gear box

The following differences distinguish OKP parts from standard parts:

1. OKP-parts require more work preparation
2. The variation on the uniform distribution for the process times is greater for OKP-

parts than for standard parts

When all the parts, standard and OKP, are manufactured they go to the assembly department and the final product is assembled.

The routing of the parts

The routing of the parts are the same for both situations, A and B. In both situations they are fixed.

The routings of all parts start with work preparation. The process times of the OKP-parts for the work preparation are in general longer and have a higher variation than the process times for the work preparation of the standard parts.
In the Eurowinch factory eight different kinds of machines are distinguished. Transport is required from one machine centre to the other and from one department to the other.
The quality control for each product is done after machines M3 and M4 are used and before and after the assembly.

The process times of the standard and OKP-parts consist of set-up times and operation times. The set-up times for OKP-parts are relatively longer than for standard parts.

Parts	WP	M1	M2	M3	M4	M5	M6	M7	M8	QC	AS
1. Hydraulic	1	2	8	3	6	10	5	9		4,7,11	-
2. Pedestal bearing	1	4,8	7	2,5	9	11	-	8	-	3,6,10,12	-
3. Warping head	1	-	2,5,9	3	6	10	-	8	-	4,7,11	-
4. Drum shaft	1	9	2,5	3	6	10	-	8	-	4,7,11	-
5. Clutch at Casing	1	-	2	3	5,8	11	7,10	-	-	4,6,9,12	-
6. Clutch Pedestal Bearing	1	-	2	3	5,8	11	7,10	-	-	4,6,9,12	-
7. Band Brake	1	2,6,9	-	-	-	3,5,10	7	4,8	-	11	-
8. Pinion Planetary Gear	1	-	2	-	3	6	-	5	-	4,7	-
9. Rope Drum	1	-	2,5,7,10	3,8	-	6,11	-	-	-	4,9,12	-
I Hydraulic Gear	1	-	3	6	8	10	-	5	4	7,9,11,13	12
II Electric Gear	1	-	2,5	-	3,9	7,11	-	8	6	4,10,12,15	13
III Steam Gear	1	-	2,7	5	3	9	-	-	8	4,6,10,12	11

Table 1: The routing of the parts

CLUSTER 1

The tasks for work preparation, quality control and transportation allocated to special staff and services in a functional lay-out

The functional lay-out:

The production department consists of 8 machine centres:

Machine centre	Number of machines
1	3 M1
2	7 M2
3	6 M3
4	5 M4
5	6 M5
6	2 M6
7	3 M7
8	1 M8

Table 2: The machine centres

In the model the machines are assumed to be equal in capacity and capability. This means that if an production order enters a machine centre it just looks for an empty machine, it does not matter which machine it is. In real-life this is probably not true, but the model becomes very complex if trying to implement a more realistic case.

In total there are 33 machines. In the factory one operator is allocated to each machine. Besides the 33 operators there are:

- 10 Quality people
- 15 work preparation people
- 2 transport people
- 6 electric winch assembly people
- 12 hydraulic winch assembly people
- 3 steam winch assembly people

The contents of the tasks for work preparation, quality control, execution and transportation

Work preparation tasks

- Work instructions and detailed drawings
  The work instructions and detailed drawings are made in a special work preparation department containing 15 professionals. The work preparation is the first process step for all the parts, standard and OKP.
  The main difference between standard and OKP parts is the average required work preparation time and the variation in the work preparation time. The work preparation time for OKP-parts is generally longer than for standard parts and has a high variation. The work preparation time for the standard parts is constant.

- Routing
  The routing is fixed for both, standard and OKP-parts. After each operation transportation is required to transport the parts to another machine centre, to the quality control or assembly department or to the store.

Detail planning tasks

- Prioritizing and scheduling
  Within SIMMEK the standard scheduling rule First In First Out (FIFO) is used.

- Planning of drawings, work instructions and helping-tools
  Not implemented.

- Allocation of operators
  Each machine gets allocated one specific operator, so-called fixed man-machine combinations.

- Distribution of the work in a work centre
  All the machines in one work centre are considered to be equal in capacity and capability. Thus all machines in a work centre are capable of producing each production order entering that specific work centre. It is however not possible to use more than one machine for one production order.

Execution tasks

- Execution
  All the people are capable of executing only one task. The operators are capable of operating only one machine.

Quality control tasks

- Quality control
  The quality is controlled:
  - after each operation on a machine of machine centre M3 and M4

- when each part is finished
- before and after the assembly of the final product

Ten professionals are responsible for monitory the quality of the all parts.

Maintenance and repairs

Not implemented

Transportation tasks

Two transport vehicles are used for all the required transportation within the factory. Two transport people are responsible for performing transportation. This is their only task as mentioned above under execution of tasks.

THE TRANSFORMATION FROM CLUSTER 1 TO CLUSTER 2

The transformation from a functional lay-out to a group technology lay-out

The group technology lay-out is made by analyzing the functional lay-out and the routings and process times of the different parts within the functional lay-out. To make the transformation from a functional lay-out to a group technology lay-out the following steps are made. They are described more extensively by Burbidge [12]:

1. Company Flow Analysis (FRN: find Factory Route Numbers)
2. Factory Flow Analysis:
   Two stages:
   - combination to unit closely associated processes into sets to form departments
   - re-allocation of machines between the departments

   (PRN: find Process Route Numbers and separate assembly operations from machining operations. (example: blank production, sheet metal, forging, welding, machining, assembly, subcontracting))
3. Group Analysis I: Form modules
   Basic technique: showing all the parts the factory makes and all the machines and other work centres used to make them (resolution of a matrix).
4. Group Analysis II: Form groups
5. Line Analysis: To put the machines within one group in the optimal sequence.
6. Tooling Analysis: To minimize setting times

The following assumptions are made during the analysis of the functional lay-out:

1. The Company Flow Analysis is not considered here because the company only has one factory.
2. The Factory Flow Analysis is also not considered in this analysis. Only the manufacturing and assembly departments are considered in the Eurowinch case. This means the Factory Flow Analysis is one abstraction level too high. The Engineering Allocation model is basically concerned with the Group Analysis. The process of forming departments is not done in this analysis, also because data is unavailable to

perform this analysis.

3. The Line Analysis is not executed, because of the fictitious data and the detailed level it does not make much sense to do this analysis. Assumed here is that the Line Analysis is done properly so that the transport times within one group can be neglected.
4. The Tooling Analysis is also not executed. It is much to detailed to do this analysis. (Generally it can be said that the tooling costs will decrease because families of similar parts will be grouped together. Standard setting tools can be developed for the different families of parts. This assumption is not implemented in the model.)

Group Analysis I: Form modules

To come to modules it is important to classify the machines. Burbidge uses the SICGE classification:

S = Special category (N=1, 20% of machines with lowest value for F)
I = Intermediate category (N>1, 40% of machines with lowest value F/N)
C = Common category (N>1, F large)
G = General category (N small, F large, dangerous, special precautions)
E = Equipment category (not important when designing groups, plentiful)

N = total number of machines of the same type
F = total number of different parts with operations on a machine type

Key machines	SICGE	F	N
M8	S	3	1
M6	I	4	2
M1	I	5	3
M7	I	7	3
M3	C	9	6
M4	C	10	5
M2	C	10	7
M5	C	12	5

Table 3: The SICGE classification

The analysis results in the following modules:

Module 1:

Key Machine : M8
Parts : I, II, III
Required machines : M2, M3, M4, M5, M7, M8

Module 2:

Key Machine : M6
Parts : 1, 5, 6, 7
Required machines : M1, M2, M3, M4, M5, M6, M7

Module 3:

Key Machine : M1
Parts : 2, 4, 8
Required machines : M1, M2, M3, M4, M5, M7

Module 4:

Key Machine : M7
Parts : 3
Required machines : M2, M3, M4, M5, M7

Module 5:

Key Machine : M3
Parts : 9
Required machines : M2, M3, M5

The modules will be used in the second part of the Group Analysis, to form groups.

Group Analysis II: Form groups

The following steps belong to the Group Analysis II:

1. Check size of the groups
2. Plan the groups and select nuclei (join modules together)
   Objective: To find families of parts which can be each completed using only its own complementary set of machines.
   To find families of parts the following criteria are used:
   1. Use many of the same machines
   2. Both use the same S type machines
   3. Both use same type and/or form of material
   4. The parts they contain have the same basic shape and/or function
   5. The parts all require the same supporting process
3. Group Selection
   1. Find obvious groups based on S + I class modules
   2. Select simplest group based on C class modules
   3. Search for additional groups
   4. Add un-allocated modules to groups
4. Allocate machines to groups

5. Elimination of exceptions
6. The load check

1. Check size
   In total 60 people are working in the work preparation, quality control, production and transport departments in the functional lay-out. 21 people work in the assembly department.
   Considering that the total number of people in a group technology lay-out will be less than in a functional lay-out and that the optimum size of a group is between 6 and 15 people, a minimum of 4 groups is required for the Eurowinch case.

2. Plan the groups and select nuclei

Group	Module	Key machine	Parts	Required machines
1	1	M8	I, II, III	M2, M3, M4, M5, M7, M8
2	2	M6	1, 7	M1, M2, M3,M4, M5, M6, M7
3	2	M6	5, 6	M2, M3, M4, M5, M6
4	3, 4, 5	M1, M3, M7	2,3,4,8,9	M1, M2, M3, M4, M5, M7

Table 4: The groups

Considerations used when designing groups:

1. The modules from the Group Analysis I
2. The required machines for the different parts
3. The throughput time of the parts
4. The required capacities (The load check)
5. The number of required people in each group
6. The number of extra machines compared to the functional lay-out

After the groups have been formed the machines are allocated to the groups. They are allocated roughly in proportion to the number of parts which use them in each group.

Group 1 : 2 M2, 1 M3, 2 M4, 2 M5, 1 M7, 1 M8
Group 2 : 2 M1, 1 M2, 1 M3, 1 M4, 2 M5, 1 M6, 2 M7
Group 3 : 2 M2, 2 M3, 2 M4, 1 M5, 1 M6
Group 4 : 1 M1, 2 M2, 2 M3, 1 M4, 1 M5, 1 M7

Each group also needs a transport vehicle.

All the assemblers are joined together in one group and considered to be capable of assembling all the three kinds of winches manufactured by Eurowinch.

CLUSTER 2

The tasks for work preparation, quality control and transportation allocated to members of the group in a group technology lay-out

The contents of the tasks for work preparation, quality control, execution and transportation

Work preparation tasks

- Work instructions and detailed drawings
  The groups are responsible for the detailed drawings and the work instructions. These instructions and drawings can, for the main part, still be done by professionals who are specialized in the work preparation. But simple tasks can also be delegated to the operators. The main point is that the work instructions and drawings in a group technology organization do not have to be as extensive and detailed as in the functional organization. There is more mutual understanding and therefore it is easier to communicate and to understand each other.
  Assumption in the model: The work preparation times of all the parts in the group technology organization are 75% of the work preparation times of all the parts in the functional organization (i.e. 25% less).

- Routing
  The routing is fixed for both standard and OKP-parts just as in the functional organization. The routing is also the same as in the functional organization.
  In real-life this is not true. In a functional organization it occurs that certain production orders enter one work centre more often than really necessary. This is because of the detailed drawings and prescriptive work instructions. This should be an advantage for the group technology organization but it is not implemented in the model.

Detail planning tasks

- Prioritizing and scheduling
  Standard FIFO is used, the same as in the functional organization.

- Planning of drawings, work instructions and helping-tools
  In the group technology organization this is all done by the operators. There is no need for a special man who plans and arranges this all.
  Not implemented.

- Allocation of operators
  The operators are multi-functional and thus there are no fixed man-machine combinations. Within the implemented model there are a certain number of operators available for operating the different machines of one group.

- Distribution of the work in the group
  The machines of the same type are considered to be equal. One production order however has to be produced on one machine. No differences with the other model.

Execution tasks

- Execution
  All the operators of one group are capable of operating all the machines of their group. There are however a limited number of members of one group who are capable of work preparation and quality control tasks.
  Remark: The set-up times for all the process steps of the routings of the production orders are in the group organization assumed as 50 % of the set-up times in the functional organization. This is caused by grouping families of parts and the use of standard setting-tools (Tooling Analysis).

Quality control tasks

- Quality control
  The quality control is now done in the group. This means that there is no need to transport the parts to and from the quality department. the quality control takes the same amount of time as in the other model. The number of quality controls is also the same. The quality control before and after the assembly of the winches is now done by the members of the assembly group.

Maintenance and repairs

- Not implemented.

Transportation tasks

- There is no transport required in the groups between the different machines. The required machines for the processes are placed in one group in an efficient sequence (Line Analysis).
  Transport however is still required:
    - from the store to the group's workspace
    - from the group workspace to the store when the part is finished
    - from the store to the assembly group
    - from the assembly group back to the store or to the transport department

  Each group is responsible for the transportation of the parts, thus they all have one transport vehicle.

DIFFERENCES BETWEEN THE CLUSTERS

The main differences between the group technology and functional model

The following assumptions, as described before in this appendix, are made within the implementation of both models:

1. The transportation time within one group is assumed to be 0, in the group technology lay-out.
2. The set-up times in the group technology organization are considered to be 50 % of

the set-up times in a functional organization.

3. The work preparation in the group technology model is considered to be 75 % of the work preparation in the functional model.

These differences and a different lay-out give the following results after running the SIMMEK simulation models:

1. The required machines
   The group technology model requires 35 machines and the functional model 33 machines. Instead of 5 M4's and 3 M7's, 6 M4's and 4 M7's are required.
   This means that the machine costs are higher in the group technology model.

2. The required transport vehicles
   In the group technology model each group needs his own transport vehicle. The group technology organization consists of 4 production groups and 1 assembly group. This means that 5 transport vehicles are required instead of 2 in the functional model.

3. The required human capacities
   In the group technology model 65 people are required and in the functional model 81 people. This is a difference of 16 people. The utilisation rate of the people is between the 86 % and 78 % in the group technology model and between 51 % and 85 % in the functional model.

4. The required human capabilities
   The people in the group technology organization need to be capable of executing all tasks. Because of the possibility within SIMMEK to define "work-places" for example work preparation and quality control, it is possible to estimate the number of people who need training in work preparation and quality control.
   In the group technology model 12 people are required for quality control instead of 10 in the functional model. For the work preparation 13 people are required instead of 15 in the functional model.

5. The utilization rate of the machines:

Functional	Group Technology
M1 : 61 %	G2M1 : 55 %, G4M1 : 67 %
M2 : 78 %	G1M2 : 81 %, G2M2 : 75 %, G3M2 : 46%, G4M2 : 69 %
M3 : 76 %	G1M3 : 91 %, G2M3 : 65 %, G3M3 : 50 % G4M3 : 72 %
M4 : 82 %	G1M4 : 58 %, G2M4 : 53 %, G3M4 : 64 % G4M4 : 66 %
M5 : 66 %	G1M5 : 55 %, G2M5 : 63 %, G3M5 : 53 % G4M5 : 71 %
M6 : 69 %	G2M6 : 53 %, G3M6 : 80 %
M7 : 76 %	G1M7 : 58 %, G2M7 : 55 %, G4M7 : 39 %
M8 : 78 %	G1M8 : 71 %

6. The throughput times (hours) and variations:

	Functional		Group Technology	
Hydraulic winch	902,9	5,5 %	767,9	10,1 %
Electric winch	976,3	7,0 %	901,8	7,8 %
Steam winch	973,0	8,3%	995,3	11,5 %

The variations are so small because of the low utilization rates of the machines.

APPENDIX 4: SADT-DIAGRAMS

Four SADT-diagrams show the flows of information and materials through the Engineering Allocation model. SADT is a functional flow modelling methodology for modelling flows and activities in a system [17].
The activities of the following four diagrams are described:

1. A0 : Engineering Allocation model
2. A1 : Flow Engineering Allocation model
3. A14 : Production and assembly
4. A15 : Calculate performance indicators

Activity 1 : Design and Construction

Input : CO 1
Customer orders in terms of estimations for:
- required manhours for the three departments (design and construction, work preparation and planning, production and assembly)
- number of new parts ("type 1 and 2")
- number of customer changes
- amount of engineering rework

Output : CO 2
Customer orders in terms of revised estimations for:
- required manhours for the three departments
- number of "type 2 parts"
- number of customer changes
- amount of engineering rework

Data 1
- required human capacities for design and construction
- job quality of the engineering work
- training need for engineers

Resources : Human capacities

Control : DC 1
The engineering effort invested in defining the functional requirements

DC 2
The engineering effort invested in reducing the number of "type 2 parts"

DC 3
The engineering effort invested in avoiding rework

Activity 2 : Work Preparation and Planning

Input : CO 2

Output : CO 3
Customer order in terms of revised estimations for:
- required human capacities for the two departments
- required machine capacities for production

Data 2
- required human capacities for work preparation and planning

Resources : Human capacities

Control : DC 3
The engineering effort invested in avoiding rework. This requires cooperation between the engineers and the professionals responsible for the work preparation.

DC 4
The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs. If these tasks are allocated to the operators only planning tasks on a higher level is left for this phase. if the five tasks are allocated to special staff and services all the work preparation and planning is done in this departments.

Activity 3 : Production and Assembly (A14)

Input : CO 3

Output : Finished products

Data 4
- required human capacities for production and assembly
- required machine capacities
- need for training for operators
- job quality of the production work
- throughput time for production and assembly
- product quality

Resources : Human and machine capacities and capabilities

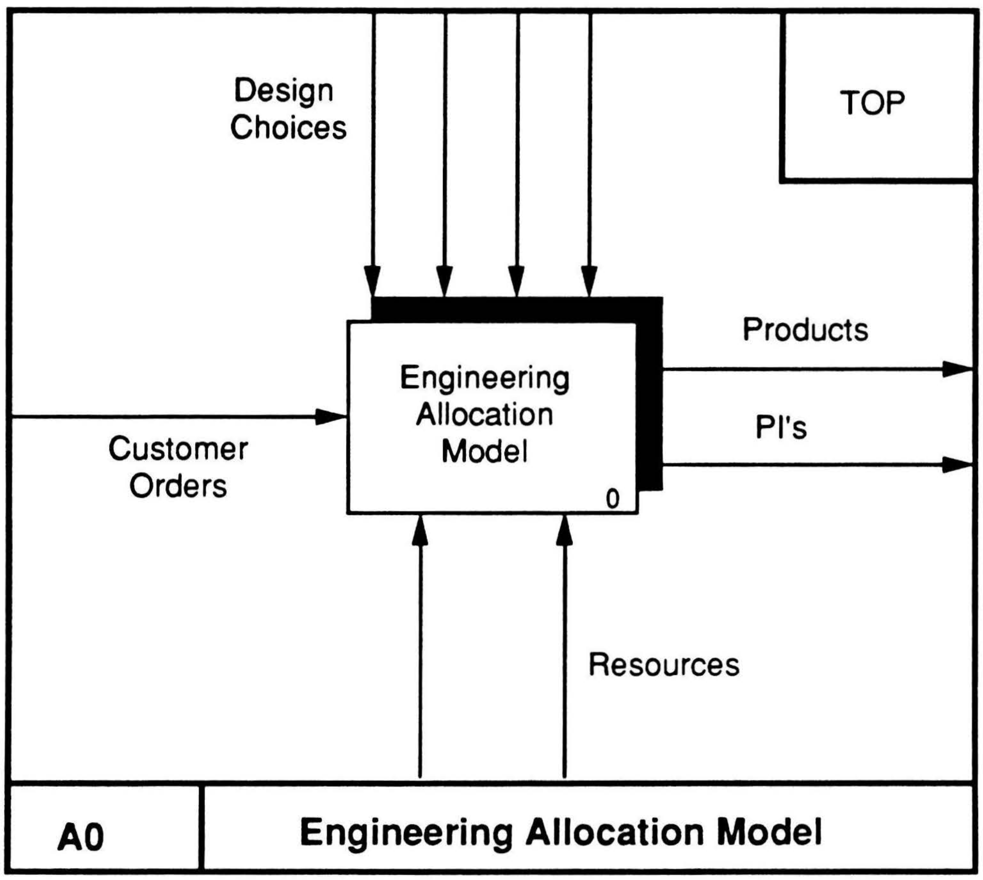
Control : DC 4
The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs.
Two different situations are modelled with regards to DC 4. These situations

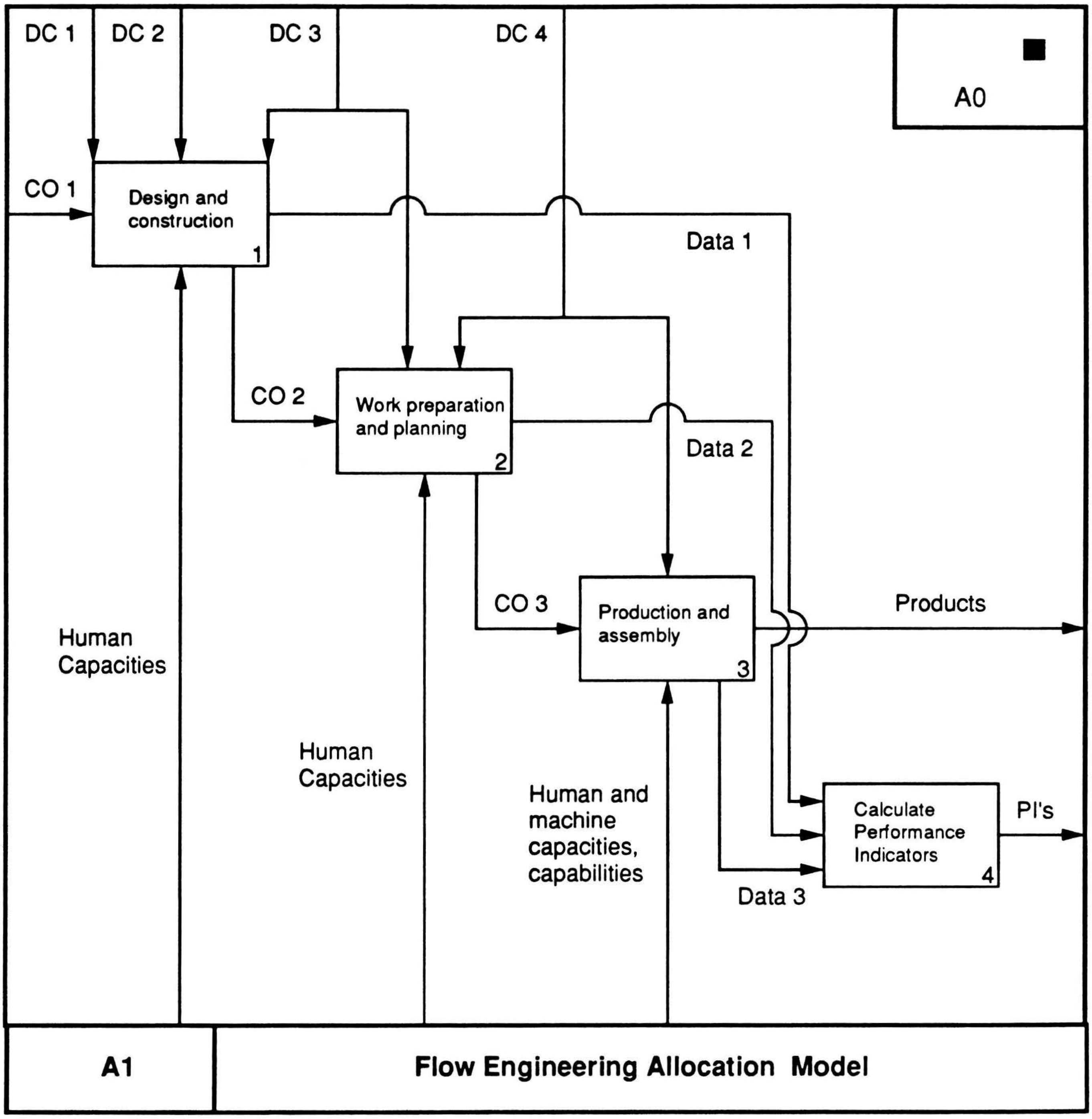
differ in lay-out and organizational structure. One situation has a functional structure and the five tasks are allocated to special staff and services. The other situation has a group technology lay-out and the five tasks are allocated to the groups.

Activity 4 : Calculate Performance Indicators (A15)

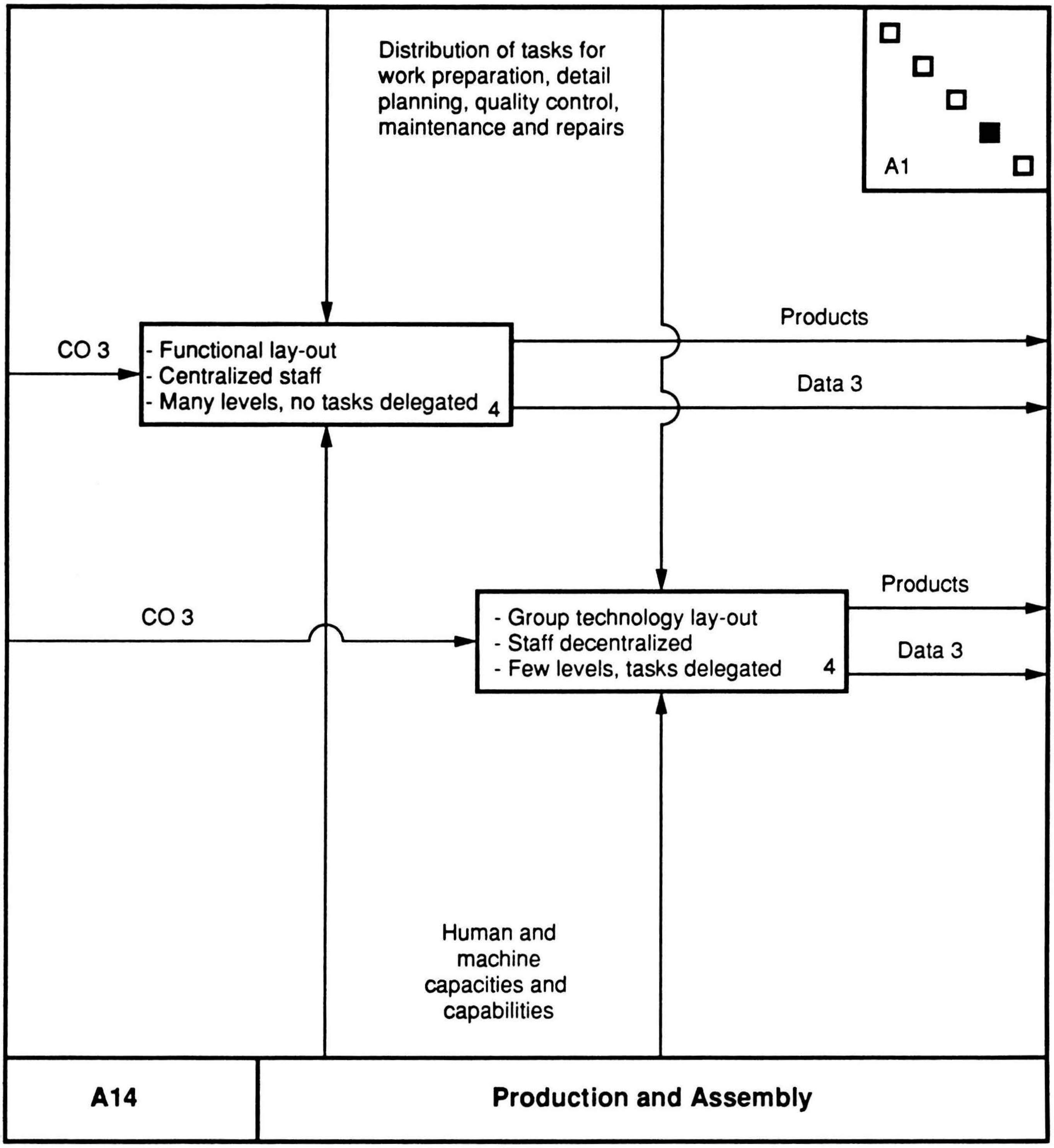
Input : Data 1, 2, 3.

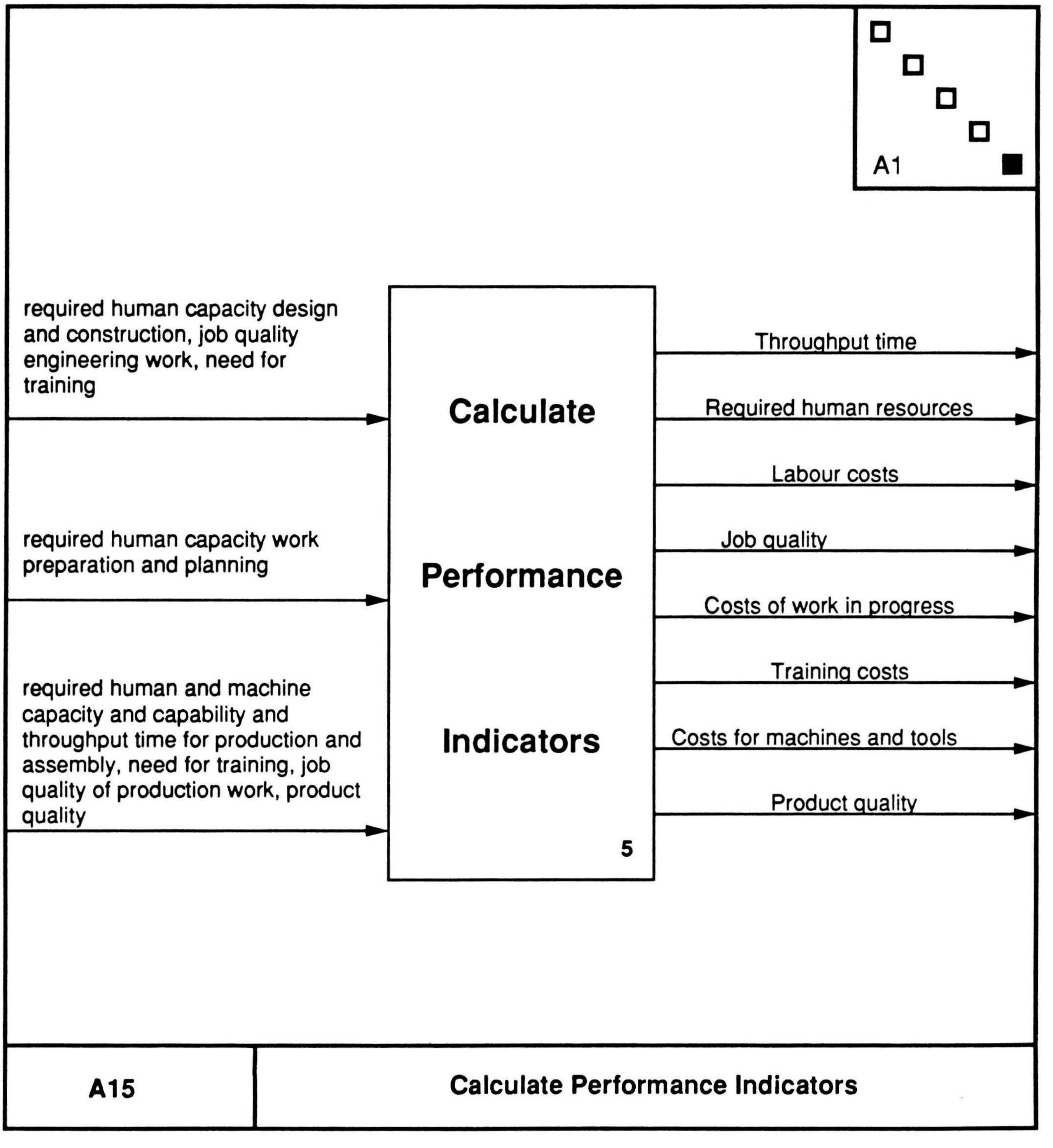
Output : Values for the performance indicators
- manufacturing and assembly throughput time
- required human resources
- labour costs
- job quality
- costs of work in process
- training costs
- costs for machines and tools
- product quality


Design
Choices
TOP
Products
Engineering
Allocation
Model
0
PI's
Customer
Orders
Resources
A0
Engineering Allocation Model



DC 1
DC 2
DC 3
DC 4
A0
CO 1
Design and construction
1
Data 1
CO 2
Work preparation and planning
2
Data 2
CO 3
Production and assembly
3
Products
Human Capacities
Human Capacities
Human and machine capacities, capabilities
Calculate Performance Indicators
4
PI's
Data 3
A1
Flow Engineering Allocation Model


Distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs
A1
CO 3
- Functional lay-out
- Centralized staff
- Many levels, no tasks delegated
4
Products
Data 3
CO 3
- Group technology lay-out
- Staff decentralized
- Few levels, tasks delegated
4
Products
Data 3
Human and machine capacities and capabilities
A14
Production and Assembly


A1
required human capacity design and construction, job quality engineering work, need for training
required human capacity work preparation and planning
required human and machine capacity and capability and throughput time for production and assembly, need for training, job quality of production work, product quality
Calculate Performance Indicators
5
Throughput time
Required human resources
Labour costs
Job quality
Costs of work in progress
Training costs
Costs for machines and tools
Product quality
A15
Calculate Performance Indicators

APPENDIX 5: THE STELLA IMPLEMENTATION

The STELLA simulation package [8,16] is used to implement the Engineering Allocation model. This section discusses how the relationships of the engineering allocation model are implemented. The pictures and equations of the STELLA model are also included. The data which is used is derived from a winch company in Bremen. Some data was however not available and thus some of data used has been fabricated.

The departments

In the model three departments are distinguished and all are similar to one another. It is sufficient to describe only one of the three to understand the implementation of the other two departments. The three departments are:

1. Design and construction
2. Work preparation and planning
3. Production and assembly

Each department has a varying amount of work in process (in manweeks). Each week customer orders arrive. For the design and construction department a random number between of 4 and 6 manweeks work arrives each week. This random number multiplied by 1.5 plus 18 manweeks arrives 5 weeks later at the work preparation and planning department. The delay of 5 weeks is the average throughput time of the design and construction phase. The random number multiplied by 2.5 plus 61 manweeks arrives 14 weeks later at the production and assembly department. The delay of 14 weeks is the average throughput time of the design and construction and work preparation and planning phases. The arrival of work in terms of manweeks at the departments has not a really high variation. This is very realistic because it is assumed that the company has a good order acceptance system.

Norms are given for the maximum and minimum amount of work in process for each department. The work in process of four weeks is added and this total amount of work in process of four weeks is compared with the maximum and minimum norms. If the total amount is bigger than the maximum norm the personnel of the particular department has to do overwork. If the total amount is smaller than the minimum norm the personnel of the department gets leave from the work place.
The capacity adjustment period is assumed to be 4 weeks, but this can be changed.

The first two performance indicators can easily be calculated. The required human capacity is dependent on the arrival of orders as described above. The labour costs are equal to the required human capacity multiplied by the wages of the employees.

The arrival of the required work in terms of manweeks is influenced by the four design choices, but this will be explained later in this section. The wages of the production and assembly personnel are influenced by design choice 4. This will also be explained later in this section.

(The exact data for wages, number of employees, etc. can be found in the STELLA equations. These numbers however are not really interesting. The numbers used for the arrival of orders are, on the contrary, certainly interesting because these number are related with the stability of the whole system as it is implemented in STELLA [5].)

The customer orders

The customer orders arrive in terms of required manweeks at each department. Initially these customer orders arrive also in terms of:

- number of changes of the customer on the specifications (random between 0 and 4)
- number of new parts ("type 1 and type 2 parts", both random between 0 and 5)
- amount of engineering rework (dependent on the number of new parts)

For each customer order estimations are made for:

- how many customer changes the order will cause if no engineering effort is invested in defining the functional requirements, and how many manweeks work (design and construction, work preparation and planning and sometimes even production and assembly) these changes will cost
- how many "type 2 parts" have to be developed if no engineering effort is invested in reducing the number of these parts, and how many manweeks of work (design and construction and work preparation and planning) the development of these parts will cost
- how much engineering rework the order will cause if no engineering effort is invested in avoiding engineering rework. (This is dependent on the total number of new parts (type 1 and 2) which remain after the engineering effort is invested in reducing the number of "type two parts")

The design choices

Design choice 1: The engineering effort invested in defining the functional requirements

For each customer order estimations are made about the amount of required engineering effort invested in defining the functional requirements to reduce the number of customer changes to 0. For each customer order this amount of engineering effort can be different, dependent on the complexity of the demands and wishes of the customer. This amount of engineering effort is defined within the STELLA implementation as 100 %. The value for DC 1 can be set between 0 and 100 %.
If for example the value 50 % is chosen, 50 % of the defined amount of required engineering effort will be invested in defining the functional requirements. Still some

customer changes will occur, but some will also be avoided (not 50 %!). Avoiding customer changes will affect the required capacities for the three departments.

Design choice 2: The engineering effort invested in reducing the number of "type 2 parts"

With the arrival of each customer order a number of new parts of "type 1 and type 2" also arrives in the system. Totally 10 parts are distinguished (Appendix 3). Each part can be a standard part or a new part of "type 1 or 2". For each customer order estimations are made about the amount of engineering effort required to reduce the number of "type 2 parts" to 0. This amount of engineering effort can be different for each customer order, dependent on the number of "type 2 parts" which initially enter the system. This amount of engineering effort is within the STELLA model defined as 100 %. The value for DC 2 can be set between 0 and 100 %.
If for example the value 25 % is chosen, 25 % of the defined amount of engineering effort will be invested in reducing the number of "type 2 parts". Still some "type 2 parts" have to be developed by the design and construction department and new work instructions for these parts have to be made by the work preparation department. But some of the "type 2 parts" are replaced by standard parts or by parts more similar to standard parts than they were initially, before the engineering effort was invested. If the value 25 % is set this does not mean that 25 % of the "type 2 parts" is standardized.
If engineering effort is invested the number of "type 2 parts" is reduced. Less "type 2 parts" means less engineering effort invested in developing new parts. It will thus affect the total amount of required engineering work. The required work for the work preparation and planning department will also decrease because less new work instructions and routings etc. have to be developed. Instead of making new ones standard work instructions and routings can be used.

Design choice 3: The engineering effort invested in avoiding engineering rework

For each customer order estimations are made, dependent on the number of the new parts, about the amount of engineering rework. Engineering rework is only caused by new parts and not by standard parts.
Avoiding engineering rework is done in cooperation with the professionals responsible for the work preparation. So not only engineering effort but also "work preparation effort" is invested. This amount of work preparation effort is directly dependent on the amount of engineering effort invested in avoiding engineering rework.
After the value for DC 2 is set and the remaining total number of new parts is calculated estimations are made for the amount of engineering effort required to avoid all the engineering rework. The estimations for the engineering effort to avoid all the engineering rework is defined as 100 %. The value for DC 3 can be set between 0 and 100 %.
If for example the value 75 % is set, 75 % of the estimated amount of engineering effort to avoid all engineering rework is invested. This does not mean that 75 % of the engineering rework is avoided.

Design choice 4: The distribution of tasks for work preparation, detail planning, quality control, maintenance and repairs in an organization

As explained in chapter 4.3, the five tasks can be allocated to:

A: operators
B: special staff

For each situation, A and B, a special work preparation and planning department and a special production and assembly department have been created. From the SIMMEK simulation runs (Appendix 3) the following results are used as input to the STELLA model:

- the average throughput time of the production and assembly department for both situations
- the average required human capacity for the work preparation and planning department and for the production and assembly department for both situations
- the average work in process for the production and assembly department for both situations

These numbers have consequences for the minimum and maximum norms of the work in process of the departments. These numbers also have consequences for the arrival of work to these departments. If for example the five tasks are allocated to operators in a group technology lay-out (Section 3.4.1) the work preparation will in general require less manhours than in a functional lay-out with the five tasks allocated to special staff and services (Appendices 1 and 3).
The wages of the operators are dependent on this DC. If the five tasks are allocated to the operators, their wages will increase with 25 %. This increasement in wages has consequences for the total labour costs. How these are calculated will be explained ion the next section.

The performance indicators

The calculations of all the PI's are explained here, although some of them already are mentioned earlier in this appendix.

1. The production and assembly throughput time

   This PI is related with the amount of work in process in the production and assembly department. The amount of work in process is limited by a minimum and a maximum norm. These norms are different for the production and assembly departments as modelled under situation A and B defined within DC 4. These norms are derived from the simulation runs in SIMMEK (Appendix 3). The relation between the work in process and the throughput time is also explained above in the section about the departments. The throughput time is specified in weeks.

2. The required human capacity

   This PI is calculated for each department and is dependent on the input of required manweeks as specified by the customer orders. This input of required manweeks is

also influenced by the four design choices as described above.
The required human capacity for each department is specified in manweeks.

3. The labour costs

The labour costs are equal to the required human capacity multiplied by their wages. The calculations to find the required human capacity are described above. Most of the wages are fixed input data and only the wages of the operators are influenced by DC 4. If the five tasks mentioned under DC 4 are allocated to the operators, their wages will increase with 25 %. The labour costs are specified in ECU's.

4. The job quality

The job quality of the engineering work is dependent on the number of manhours that the engineers use for the work specified under the first three design choices compared to the number of manhours they use for the ordinary design and construction work. Within STELLA calculations are made to come to the average "reciproce" between engineering manhours used for normal design and construction work and for engineering work as specified under the first three design choices. If this "reciproce" is equal to one, the job quality of the engineering work is defined as "very high". If no engineering effort is invested in the work specified under the first three DC's the job quality of the engineering work is defined as "low". Dependent on the values set for the first three DC's the job quality can also be "normal" or "high".

The job quality of the production work is directly dependent on DC 4. The job quality of the production work is defined as "very high" if the tasks for work preparation, detail planning, quality control, maintenance and repairs are allocated to the operators. The job quality of the production work is defined as "very low" if the five tasks are allocated to special staff and services. The job quality can in general have the following five values:

1. very high
2. high
3. normal
4. low
5. very low

5. The costs of the work in process

The amount of work in process is limited by a minimum and a maximum norm. For the implementation of DC 4 two production and assembly departments are modelled. The norms for the work in process of the four departments is different. These norms are derived from the simulation runs with the SIMMEK models (Appendix 3). The amount of work in process is simply multiplied by a specific amount of money to calculate the work in process costs. The work in process costs are specified in ECU's.

6. The training costs

   The training costs are dependent on all four design choices. If engineering effort is invested in:

   - defining the functional requirements
   - reducing the number of "type 2 parts"
   - avoiding engineering rework

   the engineers have to be trained in capabilities to cooperate, communicate and negotiate with customers, suppliers and professionals from within the company. The higher the values for the first three design choices the higher the training costs. These costs increase slowly compared to the values set for the first three design choices. If for example the values for the first three DC's are 100 %, the training costs are less than two times the training costs in the situation where the values of the first three DC's are 50 %.
   Design choice 4 fixes the training costs for the operators. If the tasks for work preparation, detail planning, quality control, maintenance and repairs are allocated to the operators they need to be trained. The training costs caused by this DC consists of a fixed amount of money for training all the production people for their new tasks at the moment they get the new tasks allocated. The training costs also consists of training costs for new employees. For this a turnover rate of 5 % is assumed. The training costs are specified in ECU's.

7. The costs for machines and tools

   The calculations for this PI are done within SIMMEK and described in appendix 7. If DC 4 is set on the value "operators" a group technology lay-out is implemented. This lay-out requires more machines than a functional lay-out. In STELLA only the costs for the extra machines are considered. This means that this PI either is zero, or is a certain amount of money, dependent on the value which is set for DC 4. The costs are specified in ECU's.

8. The product quality

   The product quality is in the implementation directly dependent on the value set under DC 4. The costs caused by production rework are taken as indicator for the product quality. In the STELLA implementation these costs have a random value between 400 and 800 ECU's per month if the five tasks are allocated to the operators. If the five tasks are allocated to special staff and services these costs have a random value between 800 and 1200 ECU's per month.

For more detailed information is referred to the model documentation [5].