Modelling and Simulation in the Early Stages of the Development Process of a Manufacturing System

A case study of the development process of a wood flooring industry

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2002:27 • ISSN: 1402 - 1757 • ISRN: LTU - LIC - 02/27 - SE
Abstract

Manufacturing Simulation, or more accurately, Discrete Event Simulation (DES), is an important problem-solving methodology for the solution of many real-world problems in the manufacturing industry. Implementation of DES has become successful in a number of industrial sectors. However, the wood manufacturing industries constitute an industrial sector where DES has still not made a breakthrough. At the same time there is a strong need for development within the sector of the wood manufacturing industries, working with the refinement of, for example, sawn boards into components and consumer products. It can be questioned, why DES cannot be used in these industries?

The objective of this work has been to investigate conditions in the development process of new wood manufacturing systems. This covers the period from when the new system mainly exists as an idea or concept, up to the point when its specifications are finalised. If DES can be integrated in these early development stages, it also highlights an unusual application area of DES, where it is used in the design process. To approach this problem the following references have been used:

- general trends and possibilities within the modelling and simulation of manufacturing systems, a technique that is undergoing rapid development.
- the unique properties of wood and wood processing that need to be considered in connection with the use of DES.
- the organisation of development activities that are extensively based on computer tools, enabling a virtual representation of the manufacturing system.

In order to validate these domains, an ongoing industrial development project has served as a reference to industrial reality. This considers a case study on the development of a new wood flooring industry, a project that covers a period of 3 years. In order to find potential use for DES, a separate simulation project was initiated. Its purpose was to verify the final specifications of the plant, which were developed using conventional industrial methods.

The simulation project showed that the specifications developed by the industry could be radically improved. Thus the simulation tool also became involved in actual design work that generated a number of design improvements to the real system. It was also shown that visualisation in the DES tool constitutes a vital feature in the design process, verifying detailed design of layout and equipment in the context of material flow dynamics. The kind of wood manufacturing studied embraces extensive material handling, which could be reproduced in detail, “true-to-scale” in 3D, by the simulation tool used.

From a technical perspective it can be established that DES constitutes a valuable resource for the development of a wood manufacturing system. However, the determining factor for whether DES will be more frequently used in the wood industry, is how it is incorporated into development activities; this is a concern for the management of the industry. Thus there is a need for a descriptive model that addresses DES, and other tools within the domain of virtual manufacturing, with regard to activities and stages reached in the development. Such a model would provide considerable guidance in the management of industrial development, not only in the wood industry.
In memory of Sajo
Acknowledgements

Finally the work on this monograph, forming my licentiate thesis, has come to an end. It has been an exciting challenge to put together my true interest in engineering, wood manufacturing and computer-aided industrial development.

The work was carried out at the Department of Engineering, Physics and Mathematics, at Mid Sweden University in Östersund, under the supervision of Professor Anders Grönlund, Department of Wood Technology, at the University of Luleå. At Mid Sweden University co-supervision has been provided by Professor Björn Esping, and Professor Håkan Wiklund.

The activities have mainly been financed by: The European Regional Development Fund, and the non-profit-making agency for the development of SMEs, ALMI Företagspartner AB in Jämtland. In this context ALMI Företagspartner deserves a particular mention; the simulation project, which was a key activity in this work, was made possible as a result of their wise decision to give it their financial support.

In the cooperation with the industrial development project, which now exists as WOW Flooring AB, a number of people have been involved. Without their great support and involvement, this work would not have been possible. In particular I would like to mention my collaboration with the technician, Mr. Lars Olsson. His knowledge and interest in a wide range of areas has enriched the dialogue within the simulation project considerably. With his positive attitude and great sense of humour he made our “simulation sessions” both creative and fun. My collaboration with Mr. Johan Ohlson, Xdin AB, Gothenburg, has also been of vital importance. His skillfulness in AutoMod, his industrial experience, and his creative mind, were determining factors for a number of important results. In cooperation with Mr. Lars Olsson, ideas of practical origin were realised in a virtual world. I sincerely appreciate the generous cooperation and great support I received during this time from Mr. Johan Ohlson and his colleagues at Xdin.

I have been encouraged by the attention given to this work in a number of contexts. In particular I would like to mention and thank the Sven Heurgren Foundation, for a second time providing me with their grant, enabling me to visit Auto Simulations, in Salt Lake City, to attend a week of lectures held by Professor Jerry Banks.

Finally I would like to take the opportunity here to express my gratitude to my colleague and co-supervisor, Professor Björn Esping, who encouraged me to embark on postgraduate studies; and also to Professor Håkan Wiklund, for discussions which have truly enriched my efforts to put this material together.

Last but not least, my appreciation is due to my supervisor, Professor Anders Grönlund, for giving me his wholehearted support.

Östersund, May 2002
Jon Johansson
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# INTRODUCTION

This first introductory chapter gives a brief overview of the problem areas and how they are linked together. It also provides the context and purpose of the study, along with some definitions.

## 1.1 Overview of the problem area

The word manufacture is from Latin *manu factus*, literally "made by hand". Manufacture is synonymous with make, fabricate, fashion, forge, form, frame, mould, produce, put together, and shape. Looking back at history, and at the present state of the manufacturing industry, it is clear that there have been three revolutions, corresponding to the three stages of industrial development. According to Wu B [1994] these stages are as follows:

The Neolithic Revolution: the age of craftsmanship

This stage of industrial development was when each individual craftsman was responsible for a total production process, from raw material to finished product, and manufacturing activities were entirely powered by human muscle. This is reflected by the fact that the word ‘manufacturing’ itself derives from two Latin words meaning literally ‘hand-making’.

The Industrial Revolution: the age of mechanisation

The Industrial Revolution took place in England and other countries in the eighteenth century and marked the beginning of the age of mechanisation. In a machine-dominated factory, the worker acquired new and distinctive skills, and his profession changed – from that of craftsman working with hand-tools to that of machine operator subject to factory discipline. The later stages of the period of mechanisation in the early years of the twentieth century were characterised by the analytical study of the production process and the development of scientific management.

The New Industrial Revolution: the age of information and automation

This revolution, characterised by the increasing application of computers for both information processing and automatic control, has led to significant changes in the techniques of manufacturing. The latest revolution in manufacturing is different; it has been brought about by advances in computer and information technologies, which put more emphasis on information and control than on hardware refinement. The similarity is that just as tools and machines increased the physical abilities of man, so the application of computers and information technology is heightening his mental abilities.

Realising that we are living and acting in a period of industrial revolution, one can reflect on many aspects of the situation. However, one thing is certain: this current revolution in the manufacturing industry is taking place at a much more rapid rate than the previous ones. The consequences of this complex and rapidly changing environment are both positive and negative. One major problem is the decision process in a dynamic world; a constantly changing environment makes the future unpredictable and complex. A decision that was right one day can be wrong the next because of new technological development and its possibilities. The purchase of software and computers is a common example, where we are all frequently exposed to these consequences. Industries face the same problem in the era of information and automation, being offered an extensive flora of computer support of various kinds. A competitive manufacturing industry must also be flexible with an immediate
response to market demands and fluctuations, and be designed to survive a number of product life cycles. It is obvious that the development of manufacturing resources under these conditions is a complex task.

For good reason major attention has therefore been given to the technique of manufacturing simulation, or more accurately, Discrete Event Simulation (DES), which is an important problem-solving methodology for the solution of many real-world problems in the manufacturing industry. Implementation of DES has become successful in a number of industrial sectors. The automotive and semiconductor industries are at the forefront of developments in this field, whereas the wood manufacturing industry is an industrial sector where DES has still not achieved a breakthrough. There may be a number of reasons for the fact that the wood manufacturing industry is behind. Nevertheless, two subjects are frequently debated in this context. First, wood is a material with various properties that influence the manufacturing process randomly. The structure of a DES model therefore becomes much more complex than in other cases when steel, polymers, or other materials are processed. Second, implementing a new technology in an organisation, or even an industrial sector such as the wood manufacturing industry, requires a qualified insight into a workflow based on modelling and simulation (M&S) of various kinds. Since M&S describes work accomplished in a virtual environment, the work procedure is radically different from the traditional one. In the effort to achieve an efficient implementation of new technology it has been found that old conceptions and attitudes among executives and their planning are often more restricting than technical functionality in new technology [Forstlin, 1992] [Andreou et al., 1999]. In this context, Klingstam [2001] states as a rule of thumb found established among people in the automotive industry that it takes one (1) part tools, ten (10) parts methodology, and a hundred (100) parts organisational development for successful implementation of a software-supported development environment in the organisation. These presumptions need to be considered in wood manufacturing industries as well as in other industrial sectors for the successful implementation of DES and other computer support within the domain of Virtual Manufacturing (VM).

In order to analyse this problem area, we have structured it into three subjects, which are clarified in more detail in the following chapters. The first subject is Industrial needs, and this deals with the situation among wood manufacturing industries. The second subject is DES used in the design process, describing the development of DES and other software tools within VM, and how they influence the workflow. The third subject is Wood-processing techniques, and here wood material and related manufacturing processes are discussed from the perspective of implementing these conditions into a DES model.

1.2 Industrial needs

The first subject is a burning issue in the wood industrial sector worldwide: the development of new manufacturing resources for refinement of sawn boards etc into components and consumer products. The following statements are to a large extent based on Scandinavian conditions, but the situation is similar in wood manufacturing worldwide.

Wood manufacturing is a part or sector of forest industries, one of Sweden’s most important industries based on a renewable raw material, the wood stock of 1999 was 3 billion m3sk\(^1\).

\(^1\) m3sk\(^*\) = forest cubic meters solid volume over bark [volume of the whole tree trunk from stump to top, including bark]
The annual growth of 100 million m³ sk, that exceeds felling by 30 million m³ sk. The export of forest industry products reached the value of SEK 94 billion in 1999, while imports of forest industry products amounted to SEK 19 billion. Thus, the trade surplus for forest industry products was SEK 75 billion. Trade by sectors with forest industry products shows the following annual trade balance surplus:

- Paper, paper goods 47 Billion SEK
- Paper pulp, recovered paper 9.6
- Sawn and planed timber 13.9
- Veneer, plywood, joinery products etc. 4.5

This can be compared with the Swedish automotive industry with a balance of trade surplus of SEK 29 billion, electronic goods and computers SEK 38 billion, or the iron and steel sector with a surplus of SEK 12 billion. [Swedish Forest Industries Federation, http://www.forestindustries.se/ ] In 1999 the production of sawn timber was around 15 million m³, of which nearly 70% is exported without any kind of refinement into secondary products such as house components, furniture etc. The amount of domestic refinement of sawn products in the manufacturing sector is unsatisfactorily low, and considerable effort is made by industries, organisations and governments to change this situation. Training and competence-development programmes, research and development projects, investment resources, and campaigns to attract qualified engineers, are some examples of efforts.

Other circumstances of importance for wood manufacturing are that the raw material sources and sawmills are to a considerable extent located in the inland of Sweden. Arguments such as employment policy, proximity to raw material sources and sawmills, less transportation, provide some incentive and explain the regional interest in building up wood manufacturing industries in these areas. On the other hand this inland region is classified by the European Community as a rural region with less developed industrial culture, a fact that indicates that industrial development is related to the unique conditions of the region.

This background highlights conditions for the development of new wood manufacturing resources. It can be assumed that this development can be greatly supported by DES and other software tools within the domain of VM. The use of DES and other VM tools is however not so frequent among wood manufacturing industries. Nevertheless the potential for the application of DES in the wood industry sector was discovered early on by Araman and Wiedenbeck [1994], particularly by utilising experience in other industries such as the automotive sector.

While DES has begun to be successfully implemented in a number of other large industrial sectors, modelling of mid-sized manufacturing operations is designated as a future application area for DES [Banks. 2000]. As for the first subject, this indicates that there is also a potential for the implementation of DES in the wood manufacturing industries, which are predominantly Small- and Medium-sized Enterprises (SME).

1.3 DES used as a design process

The second subject is concerned with DES as a branch neutral technique under rapid development that implies improved operational conditions for the Industrial Engineer (IE) to accomplish a task. While there are many methods for the analysis and design of industrial systems, DES remains the one that gives the highest level of confidence for analysing dynamic processes, i.e. influence of time. Since DES also constitutes one of many tools in a VM environment, the implementation of DES implies integration into other software. An
example is how a factory layout is often designed in a CAD system. The CAD model of the layout is then incorporated into the DES model and makes geometrical references to x-y positions and dimensions of conveyers, machinery, etc, supporting the design of the DES model. The IE can in other words be provided with DES and other VM tools to enable the embodiment of a manufacturing process or system in a computer model. Or from a more generic perspective, DES and VM are examples of tools that enable Modelling and Simulation (M&S) of a process. The potential of M&S has revolutionised the work process in a number of engineering disciplines.

- In chemical engineering molecules can be modelled, and the chemical process can be simulated in a fraction of the time compared to the real process.
- In mechanical engineering, simulation is based on a CAD model, and simulation of material stress, mechanisms, dynamic behaviour, and heat transfer are just a few examples of simulation analyses.
- In computer engineering simulation can be based on a model of a semiconductor system, and simulation is used to verify its function.
- In industrial engineering, simulation is based on various kinds of models representing the manufacturing process. Cutting processes, robotics, CAM/CNC processing, and material flows and processes in a manufacturing system, are some examples of manufacturing simulations.

Thus it becomes clear that modelling and simulation has epoch-making influences in a number of engineering disciplines. As mentioned, this development implies radical changes in the IE’s role in a project and how it is carried out with the support of VM of various kinds, as described by Andreou et al, [1999] among others.

The development of new manufacturing systems is illuminated in the previous subject by the need for development of wood manufacturing resources. The design of a new manufacturing system guides us into the case before any physical references are present. This should be seen in contrast to the development of an existent system with references from documented function and capacity by historical data. Such a development process of a new manufacturing system is traditionally based on a CAD layout and manual calculations of output. If DES is used, it is most frequently applied at the end of the development process in order to verify the new design. An alternative approach to such problems is the implementation of DES and other VM tools already in the early stage of the development process; this is defined by Klingstam [2001] as frontloading. DES is in this case integrated with other tools within the domain of VM, and all are applied together to design, develop and analyse ideas in a computer environment, i.e. in a virtual environment.

Applying DES in early development stages is however considered as unreliable because of the large amount of unknown data in a planned system, compared to simulation with existent references in a real system. On the other hand, compared with traditional development methods, it can be assumed that a DES model provides the IE with a great deal more insight into the dynamics in a material flow and the dynamics of the complete system. Visualisation of the manufacturing system in a DES model is a feature which has been radically improved over the last few years. One advantage of visualisation DES is how it supports M&S in the early development stages [Rhorer, 2001]. This second subject mainly has a technical and practical perspective on software tools and techniques, i.e. DES and other VM components. It emphasises that more knowledge is needed for efficient frontloading of DES and other VM tools.
1.4 Wood processing techniques

On the subject of wood manufacturing industries, technical conditions for wood manufacturing need to be properly reproduced in a computer model. This defines the third subject, the technical representation of a wood material and wood manufacturing techniques in a DES model. Wood products and related manufacturing processes represented in a DES simulation model imply some unique conditions that differ from manufacturing processes in general.

Wood is a biological material with a wide variability regarding both its mechanical and aesthetic properties. This influences both the yield of the raw material and the quality of the manufactured components. The quality of the raw material also influences the manufacturing process, material handling as well as machining. Thus, if there are defects in the material, e.g. knots or rot, the machine process could be interrupted or disturbed. This implies discontinuities in the process that are hard to estimate in advance. Wood also represents hygroscopic characteristics causing shrinking and swelling as a function of the humidity which results in various forms, depending on the piece of wood. Wood also has its fibre structure, which gives the material three-dimensional mechanical properties; this fibre structure has to be taken into consideration when machining. Moreover there is a potential for the application of automation in wood manufacturing processes, which often consist of large physical volumes in the material flow, and visual sorting of components. As mentioned by reference to Araman and Wiedenbeck [1994], utilisation of experience in other industries such as the automotive sector has a potential. The development of various kinds of scanning equipment for visual grading of wood components is a further example of automated equipment, which is part of an automated manufacturing line.

To summarise the third subject, due to variations in its properties the processing of wood implies an increase in the number of uncontrollable factors, compared with other industrial processes based upon materials such as steel, polymers etc. An application of DES in the design process is considered unreliable because of insufficient specification; application of DES in the design process of a wood manufacturing system makes it even more complicated and unreliable. A fully detailed description of wood properties and its processing does not necessary correspond to the actual problem in focus for DES. Thus there is a need for studies of both the possibilities and limitations when applying DES in the development process of wood manufacturing resources.
2 PURPOSE AND SCOPE OF THE STUDY

In this chapter we focus on the problem area, and define the research approach and methodology used. This chapter also defines the research question to be approached by the theoretical framework and empirical studies. Moreover, the aim of the thesis and delimitations are presented here.

2.1 Problem summary and research approach

Implementation of computer support, such as DES and other VM tools, for the development of manufacturing systems, requires planning and organisation in conjunction with a good insight into the functionality enabled in these tools. This has become of increased importance since the development of software in this area has been rapid during recent years, influencing organisation and work procedures, usability, application areas, and much more.

One of these new application areas is integration of DES into the design process, in contrast to analysis and adjustment of already completed development projects. A key issue in this context is, when and how the support of DES can be implemented in the development process, above defined as frontloading. Can it be done already in the early ideas stage; if not, when can it be done? This situation is illustrated in Figure 1. Similarities can be seen in product design based on work in a CAD system; in this case the obvious way is to start the development process by modelling the product in a CAD system. While DES is still considered a relatively new and undeveloped technique, there are still questions to analyse.

![Use of DES](image)

Figure 1 Use of DES in early development stages

In a number of respects the wood manufacturing industry is in need of development in order to be more competitive in a dynamic market. For the most part an improved refinement of the wood material into secondary products is in focus, which also includes the utilization of modern manufacturing technology.

Application of DES for the development of new wood manufacturing resources also corresponds to the common interest for implementation of DES in the design process outlined above. This forms the conditions of a special industry and development culture, with both its possibilities and limitations. One technical problem is the properties of wood and how they influence the manufacturing processes randomly, for example after decomposition in a saw, a condition that does not occur in other manufacturing industries. Properties of the wood material simply constitute conditions that make application of DES more complicated.
A further condition to consider in the wood industry is the fact that the use of various kinds of computer support are not as frequent among wood manufacturing industries as in other industries. Knowledge and experience in development work carried out in a virtual environment therefore imply a huge technological step in this branch. While questions of organisational origin belong to the executives, the organisation of development work based on a virtual environment requires good understanding. In order to achieve an efficient development process, old conceptions and attitudes among executives restrict the process of implementing new technology, more than limitations in technical functionality in the technology itself. This statement was established by Forslin [1992], and others already in the early 1990s.

Figure 2 Theoretical references and application areas

As an approach to this rather extensive problem area we have divided it into three subject areas of theoretical references:

A. Integrated development methodologies applied in the development of a new manufacturing system. This concerns the integration of three domains: computer tools for modelling and simulation, structured development methodologies, and organisational aspects of the development process.

B. Application of DES in the design process of new manufacturing systems. This is a new application area for DES, which corresponds to modelling and simulation in A.

C. Characteristics of wood material and its manufacturing process, according to requirements related to the application of DES in the development process. These conditions are what makes this study unique to wood manufacturing.

None of the three subjects can be seen as an isolated subject; they need to be integrated, which is one of the fundamental purposes of this research. The context of the subject areas is further clarified in Figure 2, illustrating theoretical references of integrated development (A) by the three circles, and the focus of DES (B) as a sector of computer tools. The application area considers development of new manufacturing systems (C), which in some respects are related to manufacturing industries in general, but also focus on the unique conditions of wood manufacturing.
The arrows in Figure 2 illustrate the reciprocal action between both theoretical references and industrial reality. Reciprocal action between industry and the academic world is further illustrated in Figure 3, showing the aim to provide applicable results for industrial application in a long-term perspective.

2.2 The research question

This thesis is part of the research that focuses on efficient implementation of computer support in the development process of new mid-sized manufacturing systems, representative to wood manufacturing in general. Based on the presumptions of the problem area defined, one main question guides the research.

How can the use of DES support a more efficient development process in the design of a new manufacturing system for wood products

The part of the development process we are concerned with is the early development stage of a new manufacturing system, which is defined here as the period from the idea stage to the final design decision. Generally this is a period of design freedom but uncertainty, when for example physical reference systems are not available for validation of concept ideas. This is the context in which DES is considered, to support to the design process and make it more efficient.

The meaning of a more efficient development process concerns development of better solutions in a minimal development time, at a lower cost. Apart from technical functionality in the manufacturing process, a better solution also implies an efficient start-up time of a new manufacturing system.

2.3 Aim of the thesis

This thesis includes a survey of the industrial conditions on the basis of the problem area outlined in the introduction, partly by means of theoretical references, partly by an industrial case study.

The theoretical references provided are partly influenced by the research frontline of the manufacturing industry in general, and partly by findings in the industrial case of wood manufacturing that was studied, as illustrated in Figure 3. It is mainly observations in the industrial case, during the time this study has been going on, which have influenced the essential elements of the theoretical framework. This is also illustrated in appendix 1. Based on these conditions the aim of this thesis is to provide better guidelines for the application of DES in the design process of a new manufacturing system.

Apart from interested parties in the academic world, there are also two main groups of stakeholders interested in the issues in this study.

- Wood manufacturing industries and their executives responsible for product and process development.
- Authorities, organisations and consultants who make decisions, initiate or participate in development projects for wood industrial development.

There is an aim to provide these groups with an extensive reference for managing manufacturing development projects based on the utilisation of DES in a VM environment.

Conditions for wood manufacturing are emphasised in a number of respects, but it should be put forward to these groups that VM is a generic support, and application can be found among a number of other manufacturing industries.
It can be assumed that the process to understand and organise industrial development projects can be supported to a large extent by the use of VM. This thesis aims to guide groups mentioned above into the features of virtual manufacturing, which can sometimes be perceived as quite abstract without experiencing it on a computer screen. An improved understanding of VM applications is crucial because it has been reserved for large industries for a long time. With the extensive development of soft- and hardware, lower prices and improved usability of DES software have made this technology available to smaller industries as well.

2.4 Research methodology

Besides studies of theoretical references, this research is based on an ongoing industrial development project of a wood flooring industry. This industrial project started in 1997 and the development process has been observed up to the time when the new plant was established in 2000. During this period, activities in the ongoing project have influenced the theoretical references chosen, illustrated by the arrows in Figure 3.

The later part of the development project is a period of more intense activities, defined in Figure 3 as the “Simulation project”. This refers to the time when the final design decision was taken concerning the layout of the plant, and the plant was ready to be built. The simulation project was then established as a stand-alone project for a number of reasons. One reason was to evaluate the capacity of the new manufacturing concept on the basis of a snapshot of initial specifications and manual calculations of production capacity.

The figure below also illustrates how results and conclusions in this thesis are composed of a synthesis between both theoretical and industrial references. One of the aims of this approach is to achieve results that are based and applicable in both industry and the academic world.

![Figure 3 Influences from industrial activities](image-url)

To collect information concerning the ongoing development process, there has been a continuous dialogue with the entrepreneur and brain behind the project since the idea stage in 1997. The documentation and analysis of the development process is based upon qualitative interviews, supported by methodologies defined by Westlander [2000] and Kvale [1997].
The simulation project is of a more quantitative and applicable character; focusing on specifications and practical cases of problem solutions, design criteria etc, related to the application of DES in the design process. Results from this part of the study are based on a close cooperation between the industrial group and academics; they are of practical origin and are applicable to real-world problems in the manufacturing industry.

2.5 Disposition of the thesis

In addition to this chapter and the previous one, the thesis consists of totally 9 chapters in all. The context is illustrated in appendix 1, and clarified by the following:

Chapter 1 Introduction

This first introductory chapter gives a brief overview of the three problem areas and how they are linked together. It also provides the context and purpose of the study, along with some definitions.

Chapter 2 Purpose and scope of the study

In chapter 2 we focus on the problem area, and define the research approach and methodology used. This chapter also defines the research question to be approached by the theoretical framework and empirical studies. Moreover, the aim of the thesis and delimitations are presented here.

Chapter 3 Theoretical framework

In this third chapter the theoretical frame of reference is built up. Besides prior research work in the areas concerned, the choice of references is also influenced by the ongoing activities in the industrial development project used as a case study.

Chapter 4, 5, 6, The industrial reference case

In chapter 4 the industrial development project is used as an industrial reference project, and is presented in detail, together with an outline of the study and how it is carried out. The study focuses on two subjects: the actual development process, and possibilities for application of computer support. Results from these two subjects are presented in chapters 5 and 6.

Chapter 7 Analysis and reflection

In this chapter results from chapter five and six are discussed and analysed with reference to the theoretical framework and the research question on which this thesis is based.

Chapter 8 Final conclusions and further research

Referring to the study’s research question, chapter 8 finally summarises the results and states the conclusions of the study, and proposal for further research.

2.6 Delimitation

The following delimitations have been made:

- Only one development project is studied, and it is a temporary and improvised organisation, not to be confused with a permanent development organisation in a corporation.
• Results from this research are in some respects of a general character and useful in various manufacturing industries, but are in other respects limited to the wood manufacturing industries.

• Only one type of DES software is used in the simulation case. Results and conclusions are therefore in some respects subjective and intimately related to the actual DES software that was used.

• No financial issues are considered regarding the investment of alternative manufacturing solutions.

Regarding VM, which is a wide and in some respects abstract area, this study does not aim to provide a complete reference. Nor do we focus on the theoretical and technical depth of DES techniques.

2.7 My own preunderstanding and inspiration sources

I have entered this problem area due to my background from industry, where I worked with design and development of machinery for wood processing. These previous experiences in industry mainly concerned the development of process equipment for the sawmill industry during my employment and co-operation with the sawmill producer, ARI AB, Örnsköldsvik, Sweden. This work included machine and tool design, and a number of applications where visual scanning techniques were integrated into mechanical equipment.

One product that I worked on and that was given major attention is the automatic log feeder. This machine automatically scanned the log profile using video techniques, and positioned the log correctly sideways and by rotary angle before it was fed into the primary saw machine [Royal Sweden Academy of Engineering Science Annual Book of 1988, page 105]. Further design work done in other contexts is a table saw, and table router, both intended for carpentry and furniture making. Furthermore, reconditioning of used machine equipment that has been installed in my carpentry shop has been my spare time interest since the early 80s, in connection with the design and making of furniture.

![Figure 4 The automatic log feeder, KSI-6 (ARI AB) [Source: The Royal Sweden Academy of Engineering Science Annual Book of 1988, page 105]](image)

All in all, these previous experiences in wood processing and machine design have provided a great source of inspiration for me in my work on this thesis, giving me the potential of linking practical work with theories.
3 THEORETICAL FRAMEWORK

In this third chapter the theoretical frame of reference is built up. Besides prior research work in the areas concerned, the choice of references is also influenced by ongoing activities in the industrial development project used as a case study. The aim of this chapter is to provide references in the wide scope of issues arising in this case, particularly because of the multidisciplinary attempt to study the development process. The multidisciplinary approach to the problem area is mainly due to the influence of my studies in integrated product development at the Swedish Design Research and Education Agenda [ENDREA 2001].

However, references found within the domain of integrated development methodology are mostly related to product development. Consequently, by categorising a manufacturing system as a complex product or a system, some of these development methodologies also become applicable in the development of a manufacturing system.

3.1 The development process

3.1.1 A generic development process

Development is an interdisciplinary activity requiring contributions from a number of disciplines organised within a development team. Regardless of whether it is a product or a manufacturing system that is under development, there is a need for an efficient and creative arrangement of the development process. There have been many attempts to draw up maps or models of the development and design process. A generic product developing process can be categorised in different stages as illustrated in Figure 5 by reference to Ulrich and Eppinger [1995]. The process starts with some kind of demand from the market, new technology, or other assumption that initiates and defines specifications for concept development. Successive stages show how the development process can be divided into stages of its advance to production. However, this model has its origin in product development, but also provides a reference to further discussions in manufacturing system design and how it can be structured.

![Figure 5 A generic development process](Ulrich and Eppinger, 1995)

Within the development process a design is fulfilled. Models of the design process are often drawn in flow-diagram form, illustrating the progress of the design process from one stage to the next. A simple four-step model of the design process with feedback loops showing the
iterative returns to earlier stages is illustrated in Figure 6 [Cross, 1994]. The loop is necessary, assuming that the evaluation stage does not always lead directly onto the communication of a final design.

![Figure 6 A simple model of the design process](image)

A map of the design process provides a generally structured model, which refers to a step-by-step approach and often provides templates for the key information systems used by the team. Although the methodologies are structured, they are not intended to be applied blindly; there is also room for creative methods. The methodologies are a starting point for continuous improvement. Teams should adapt and modify the approaches to meet their own needs and to reflect the unique character of their institutional environment.

Some of these models describe the sequences of activities that typically occur in designing; other models attempt to prescribe a better or more appropriate pattern of activities, i.e. describe or prescribe models, [Cross 1994]

- **Descriptive Models** of the design process usually emphasise the importance of generating a solution concept early in the process, thus reflecting the ‘solution-focused’ nature of design thinking. This initial solution ‘conjecture’ is then subjected to analysis, evaluation, refinement and development. Sometimes, of course, the analysis and evaluation reveal fundamental flaws in the initial conjecture and it has to be abandoned; a new concept has to be generated and the cycle started again.

- **Prescriptive Models** usually offer a more algorithmic, systematic procedure to follow, and are often regarded as providing a particular design methodology with the aim of encouraging designers to adopt improved ways of working. Many of these prescriptive models have emphasised the need for more analytical work to precede the generation of solution concepts. The intention is to try to ensure that the design problem is fully understood, that no important elements of it are overlooked, and that the ‘real’ problem is identified. There are plenty of examples of excellent solutions to the wrong problem: therefore prescriptive models tend to suggest a basic structure to the design process of analysis-synthesis-evaluation, in order to maintain the focus on the actual problem.

### 3.1.2 Structured models of the design process

Design processes of various kinds are widely discussed in literature such as Phal and Bietz [1996], Hubka [1996], Ulrich and Eppinger [1995], Shu [1990] and French [1988], among others. All these references provide structured methodologies of various kinds in order to achieve a more efficient development and design process. For example, according to Ulrich and Eppinger [1995], structured methodologies are valuable for three reasons.

- First, they make the decision process explicit, allowing everyone in the team to understand the decision rationale and reducing the possibility of moving forward with unsupported decisions.
- Second, by acting as a "checklist" of the key steps in a development activity they ensure that important issues are not forgotten.

- Third, structured methodologies are largely self-documenting; in the process of executing the methodology the team creates a record of the decision-making process for future reference and for educating newcomers.

As a reference to some of these more complex models, the following model of the design process by French [1998] provides a generic overview. In the model illustrated in Figure 7, the circles represent stages reached, or outputs, and the rectangles represent activities, or work in progress. The model contains the following activities: Analysis of the problem, Conceptual design, Embodiment of schemes, and Detailing.

![Figure 7 Detail model of the design process [French,1998]](image)

The process begins with an initial statement of “Need” and the first design activity is Analysis of the problem. French emphasises that: The analysis of the problem is a small but important part of the overall process. The output is a “statement of the problem”, and this can have three elements:

1. A proper statement of the design problem
2. Limitations placed upon the solution, e.g. codes of practice, statutory requirements, customers, standards, date of completion, etc.
3. The criterion of excellence to be worked to.

These three elements correspond to the goals, constraints and criteria of the design brief. The activities that follow, according to French, are then:

**Conceptual design:** This phase takes the statement of the problem and generates broad solutions to it in the form of schemes. This phase places the greatest demands on the designer and this is where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together, and where the most important decisions are taken.

**Embodiment of schemes:** In this phase the schemes are worked up in greater detail and, if there is more than one, a final choice between them is made. The end product is usually a set
of general arrangement drawings. There is (or should be) a great deal of feedback from this phase to the conceptual design phase.

**Detailing:** This is the last phase, in which a very large number of small but essential points remain to be decided. The quality of this work must be good, otherwise delay and expense or even failure will be incurred; computers are already reducing the drudgery of this skilled and patient work, and reducing the chance of errors, and will do so increasingly.

This model by French may sound very similar to a conventional design process, but the emphasis here is on performance specifications logically derived from the design problem, generating several alternative design concepts by building up the best sub-solutions and making a rational choice of the best of the alternative designs. Such apparently sensible, rational procedures are not always followed in conventional design practice.

### 3.2 Virtual tools used in the design process

#### 3.2.1 Brief tour of virtual references

Modern engineering work is today greatly influenced by all kinds of computer support for modelling and simulation of various kinds. As a result of this development in computer technology, the word *virtual* has become increasingly used in a number of contexts. “Virtual”, comes from the Latin word *virt s*, which means existing in essence or effect though, not in actual fact or form. For example, in the representation of a physical object on a computer screen, the observer perceives a virtual object. If the object, that could be a CAD model, is also represented in its environment, and real-time interaction with the observer is provided, it can be categorised as Virtual Reality to some extent. This virtual representation refers to a wide span of applications, from a simple CAD model to the fully functional VR application with the observer immersed in an interactive simulation process.

A virtual 3D world can be created using various tools, such as modelling in CAD software. The model or geometry is then imported into a real-time simulation tool in order to "make it live". This is one of the major differences from animation tools in which the entire experience is predetermined and cannot be changed by the user. The term Virtual Reality (VR) can be broadly defined as the ability to create an interaction in cyberspace, i.e. a space that represents an environment, which is very similar to the environment around us [Banerjee, Zetu, 2001]. In a VR world the entire experience is rendered in real-time, where the user's actions affect the experience moment by moment. The VR world can be experienced in different ways, in a visual, auditory and tactile (touch and force) manner. VR technology is currently used in a broad range of applications. The best known applications are flight simulators, walk-throughs, video games, and medicine (virtual surgery). Sometimes users augment the experience with 3D stereo glasses, gloves, helmets or a tracking system in order to interact better with the environment. From a manufacturing standpoint, some of these attractive applications can include training, collaborative product- and process design, facility monitoring, and management.

VR is a sense of realism and the VR world should be interactive, intelligent, and in real-time. VR can be realised by advanced systems, to provide the most common way of experiencing VR, i.e. sitting in front of a desktop computer screen.

#### 3.2.2 Virtual manufacturing

Virtual Manufacturing (VM) refers broadly to modelling and simulation of manufacturing systems and components, which could include effective use of audiovisual and other sensory features to simulate or design alternatives for a manufacturing environment.
The motivation is to enhance our ability to predict potential problems and inefficiencies in product functionality and manufacturability before real manufacturing occurs. According to Banerjee and Zetu [2001], some areas that can benefit from the development of virtual manufacturing include the following:

- Product design
- Hazardous operations modelling
- Production modelling
- Process modelling
- Training
- Education
- Information visualisation
- Telecommunications and tele-travel

In product design, the term virtual (or digital) prototyping has become frequently used in the context of rapid prototyping. By virtual prototyping, it is possible to test a non-physical product in a virtual environment. Simulation of the product and how it will behave in a certain environment can be done by using solid mechanics, dynamics and fluid mechanics. Based on the virtual prototype, rapid prototyping can also imply manufacturing of a physical 3D model by rapid prototyping machines, building prototypes by precise deposition of layer upon layer of powdered metal or polymers.

Another term that is sometimes mentioned in the context of virtual manufacturing is agility manufacturing, sometimes defined as a structure within which agility is achieved through the integration of three primary resources: organisation, people, and technologies. A way to achieve this is through innovative management structures and organisation, a skill base of knowledgeable and empowered people, and flexible and intelligent technologies. Whereas agility focuses on the ability to make rapid changes in products and processes based on the voice of the customer, virtual manufacturing provides a means for doing so (Banerjee and Zetu, 2001).

### 3.2.3 Standardised information

Shared information is a key to efficient co-operation both locally, within a corporation and globally. So-called PDM systems (Product Data Management) provide a data base structure for management of the development process. Originally oriented to products, the virtual prototype or the actual CAD model can here be used as an information carrier when it is sent into other computer systems. Based on the geometrical information of the CAD model, further product information such as analysis of results, maintenance documentation, bills of materials, processing and assembly information are examples of information that can be implements in the product model. In order to achieve compatibility among the flora of computer systems and their individual data format, a standard and neutral computer interpretable format is needed. Examples of geometrical standard exchanges format are the IGES format and the DXF format from Auto Desk that has become an industrial standard in some areas. Nevertheless, these formats do not provide complete compatibility between systems and do not fulfil the function as information carrier of the product.

To enable different computer applications to share and exchange all information about a product model through its lifecycle the STEP standard has been developed. STEP, the Standard for the Exchange of Product Model Data, is a comprehensive ISO standard (ISO
10303) that describes how to represent and exchange digital product information. Digital product data could contain enough information to cover a product's entire life cycle, from design to analysis, manufacture, quality control testing, inspection and product support functions. In order to do this, STEP must cover geometry, topology, tolerances, relationships, attributes, assemblies, configuration and more. To accomplish this ambitious goal, STEP has been constructed as a multi-part ISO standard. The basic parts are complete and published, while more are under development. These parts cover general areas, such as testing procedures, file formats and programming interfaces, as well as industry-specific information. The most important aspect of STEP is extensibility. STEP is therefore based on a language that can formally describe the structure and correctness conditions of any engineering information that needs to be exchanged. Two of the key reasons for why the ongoing development of STEP is important are that it is based on a language (EXPRESS) and can be extended to any industry. The EXPRESS language describes constraints as well as data structure. STEP is international, and was developed by users, not vendors. User-driven standards are results-oriented, while vendor-driven standards are technology-oriented [SwedSTEP, 2001].

A further development of the STEP standard also integrates information about the manufacturing system related to a product. This implies that information on various kinds of manufacturing simulation, such as simulation of robotics, geometry simulation and process simulation by DES, will be standardised and exchangeable between computer systems [Rosen and Johannsson 2000].

Recent advances in broadband networks and Internet communications are opening up new applications for tele-collaborative virtual environments in these areas [Johannesson and Kempinsky, 2001]. Internet communication can be seen in conjunction with terms like e-business, and similarly, the development of information standards might result in engineering environments such as e-development, e-design, e-manufacturing etc. In this context standardised information is of crucial importance to enable information exchange.

3.2.4 Virtual manufacturing systems

The design support for manufacturing systems based on virtual environments has been radically improved during the last few years by the development of Discrete Event Simulation (DES), and other closely related tools for design and analysis. There is a wide range of software technologies available, supporting design and analysis of a manufacturing system, which come under the collective term Virtual Manufacturing (VM). The set of tools and their application areas is a unique combination for each company and their needs. Application of VM frequently occurs in the automotive sector. As a reference, the virtual environment at Volvo consists of tools listed in table 1 and their application areas according to Klingstam [2001].

These application areas represent the domain of the product, the work cells, and the plant. These three domains enable the creation of both a "virtual product" and a "virtual factory" (digital factory).
Table 1. Overview of common tools for VM applications [Klingstam 2001]

<table>
<thead>
<tr>
<th><strong>Common tools</strong></th>
<th><strong>Examples of main Application</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>4D Navigator [Dassault]</td>
<td>Digital Mock-up [product]</td>
</tr>
<tr>
<td>CCPlant [Dassault]</td>
<td>Layout [work cell/plant]</td>
</tr>
<tr>
<td>ERGOMAS [Delmia]</td>
<td>Work cell layout [work cell/plant]</td>
</tr>
<tr>
<td>Envision [Delmia]</td>
<td>Assembly, Ergonomics [work cell]</td>
</tr>
<tr>
<td>IGRIP [Delmia]</td>
<td>Robotics [work cell]</td>
</tr>
<tr>
<td>Quest [Delmia]</td>
<td>Material Flow [plant]</td>
</tr>
<tr>
<td>Vismockup [EIA]</td>
<td>Digital Mock-up [product/work cell]</td>
</tr>
<tr>
<td>Jack [EIA]</td>
<td>Ergonomics [work cell]</td>
</tr>
<tr>
<td>Visfactory [EIA]</td>
<td>Layout [plant]</td>
</tr>
<tr>
<td>Robcad [Tecnomatix]</td>
<td>Robotics [work cell]</td>
</tr>
<tr>
<td>eM Plant [Tecnomatix]</td>
<td>Material Flow [plant]</td>
</tr>
</tbody>
</table>

A subsequent question might be: What is the best setup of VM applications for various kinds of needs. No answer has been found to this question, and it might not be easy to give an answer while changes are continuously being made as a result of the rapid development of DES and other applications within the domain of VM.

3.2.5A strategic perspective on VM

Today, there is a strong need for companies to adapt to the new market forces they face under the conditions of globalisation. Companies need to restructure their business organisation in order for their production processes to be adaptable to continuous and rapid changes in customer demands and an evolving definition of quality. This leads to the strategic concept of agility, described as the capability to operate profitably in a competitive environment of continually, and unpredictably changing customer requirements. Several approaches such as just-in-time, lean manufacturing and concurrent engineering have been developed to cope with this increasing need for agility.

In this context, VM has raised grand expectations and interest among those who work with design and development of manufacturing systems. The need of the Industrial Engineer (IE) for a support to handle large numbers of parameters is fulfilled in many ways by the development of VM. Specifications of raw material, products, processes, set-up time, batch sizes, machinery and tools, and schedules for manual operation and service can today be implemented in a model of the real manufacturing system. Furthermore, the IE has to be able to manage the complexity and dynamics of non-controllable parameters such as machine breakdown, lack of raw materials and components, rejection and remanufacturing, and the human factor, which can be analysed by DES. A manufacturing system must also be designed to live through a number of product lifecycles and have the flexibility to adapt efficiently to new manufacturing techniques and strategies towards market demands.

In enabling the IE to manage this complexity, VM certainly has potential to support the IE's work. However, we still do not know the best way of utilising all the new digital features, and software designers are continuously coming up with new applications. Applications that offer alternative work techniques for managing information, modelling of geometry and processes, simulation and analysis of complexity, just to mention a few areas. Integration of these software technologies and implementation of VM in the development organisation does not always run without friction, according to Klingstam [2001] among others.
However, the friction of implementing computer technology in an organisation was pointed out much earlier by Forslin [1992], and by references to a number of authors. It has been discovered that the potential for using computers is more limited by old conceptions and attitudes, than by technical problems. Since executives have little or no experience of work with computers, their visions will stay within their old frames of reference [Forslin, 1992]. A further statement corresponding to this is given by Klingstam [2001] as a rule of thumb established among people in industry, to describe the effort to implement new technology, such as efficient use of VM technology in the organisation. This rule says that it takes one part tools, ten parts working procedures, and one hundred parts organisational development for successful implementation of such techniques.

3.3 Discrete Event Simulation

3.3.1 Overview

Given the context of VM in previous chapters, DES is described here in more detail, mainly corresponding to the modelling stage, i.e. design of DES model, and the effort to improve model quality in early development stages. Looking back, the use of DES has been applied to manufacturing problems for about 40 years. But for most of that time, it has been the domain of a few specialists, not accessible for industrial engineers without knowledge of unique simulation languages. Changes in this area came as a result of the fast development of personal computers in the late 1980s, and later, along with decreasing prices of components during the 1990s. A further condition for this change is the development of a graphics user interface (Windows) which influenced the design of DES software and made it more user-friendly. This also denotes graphical support in model design and examination of the actual simulation.

Simulation of manufacturing systems, particularly of logistics and production flows, has increased considerably during the late 1990s. This can in particular be seen in the automotive field, where simulation has deeply penetrated automotive manufacturing for capital project analysis, and for analysis and operations management in semiconductor manufacturing. Another major area is automated material handling, and in particular warehousing and distribution applications, often applied for analysing and demonstrating new systems [Banks 2000]. However, within the context of manufacturing system design and development, practical use of DES has been slow to catch up with the state-of-the-art level of research. This has been shown in work done in several highly industrialised countries, including Sweden, Germany, Great Britain and Japan [Eriksson 2000, Holst and Bolmsjö 2000, Hirschberg and Heitmann 1997, Hlupic 1999, Umeda and Jones 1997].

Fields or branches where DES has opportunities for a further successful implementations in the future are health care, business process analysis, service industries such as call centres, fast-food retail, and entertainment facilities. Other prime candidates are transportation systems such as streets and highways, pedestrian movement, freight and passenger rail, airport and airspace simulation, water transportation, and port facilities. Other more relatively untapped areas are pharmaceutical and chemical manufacturing, mining and mineral processing, printing and publishing, and modelling of mid-sized manufacturing operations. [Banks. 2000] Trends can also be seen toward modules for specific applications for manufacturing, business process and more. Output analysis capabilities have also been integrated into many software packages, enabling support to experimental planning and statistical analyses of simulation results. These additional features in the DES software reduce the specific knowledge required for analysing statistical data [Holst et al, 2000].
There are about 50 DES tools on the commercial market today, in a price range from $50 up to $40,000. In the Simulation Software Survey of February 2001, by Lionheart Publishing, Swain [2000], 47 simulation packages are listed, making it one of the larger surveys in the series. Other examples of surveys and overviews of DES software are provided by Nwoke and Nelson [1993], and Klingstam and Gullander [1999], among others. All simulation packages have strengths and weaknesses. Some are extremely good at describing specific industries or systems for manufacturing, material handling, robotics etc; other DES tools are used in processes of a general character.

It is easy to find a good simulation package on the market today that provides the ability to model just about any system encountered. Continuous improvements in simulation software can now be found in better usability, helping to build models faster and more efficiently and thus shorten project schedules. For example, simulation technology can allow both clients and consultants to work with models more efficiently and effectively over the web without having to be physically in the same location [Banks, 2000].

To achieve clear communication between a simulation expert and a client, visualisation of both the modelling and simulation stage has become a key factor Rhorer [2000]. In collaboration with a client not fully initiated in DES techniques, such as some wood manufacturing industries, it can be assumed that the dialogue could be radically improved by visualisation. This is a matter of verification and validation supported by visualisation during both the modelling stage and the actual simulation. These subjects are further discussed below; in chapter 3.3.3 in the context of verification and validation, and later in chapter 3.4.3 in the context of models and prototypes.

3.3.2 Usage areas in manufacturing design and development

Application of DES can be found in many different fields and branches, as stated in the introduction. Three typical problem characteristics where DES has been used in the manufacturing industry can then be defined as follows [Senge and Fulmer, 1993]:

I. Explorative studies of existing systems to improve them

II. Studies of existing systems with some changes made to them, similar to the first purpose but used to validate a specific alternative, e.g. a proposed investment

III. Design and validation of new systems, i.e. to study more conceptual ‘what-if’ questions.

The traditional use of DES, or at least the typical kind of problem where DES is frequently used, is related to points I and II. In both these cases, simulation studies are based on existing systems, serving as a key reference source providing the modelled system with accurate data. DES is at least not seen as a design tool, supporting a structured and creative development process of new manufacturing systems. DES used in the design process is more used to verify existing solutions, rather being integrated in the development process, as the third point above indicates.

Nevertheless the rapid development of DES also implies alternative application areas by multi-functional DES tools, conditions that radically influence usability in alternative applications areas. For example focusing on the early development stages, visualisation and animation is of particular interest because it enables an embodiment of a manufacturing system that still does not exist in reality. Moreover, multi-functional features are found in some DES tools. Purposed for manufacturing, these tools enable the handling of large complex models, optimisation, interactivity in the simulation process, emulation of PLC control system and robotics, distributed modelling and simulation through web interface, dimensional exact visualisation and representation of static and moving 3D objects, collision
detection in material flow, 3D animation of an ongoing simulation process and more. The development of DES tools in recent years also indicates for example a closer integration towards additional software supporting the modelling process. An example of practical use is integration of CAD, 2D objects used for layout and 3D objects for equipment and products.

Formulation of the problem and the modelling phase thus becomes something that is intimately related to the functionality represented in the simulation tool used. This means that new software features are continuously offered in alternative DES tools that enable alternative work methods and techniques to be used, and DES is a versatile tool. In this matter, DES is often classified or related to different industries or services. A non-branch related classification of uses of simulation in different ways includes the following [Harrell & Tumay, 1995]:

- Systems design
- Systems management
- Training and education
- Communication and sales
- Public relations

3.3.3 Verification and Validation

While the focus in this thesis is on development of new manufacturing systems, some conditions are of unique concern. The fact that the planned system only exists by specifications and 2D layout, which is a limited media, is most critical. With the definition frontloading, established by [Klingstam, 2001], it is desirable to apply VM tools early in the development process. Thus VM provides the IE with an extensive toolbox supporting a more efficient development process. One of these tools is DES, considered to be difficult to apply in the early development stages because of insufficient information on the planned system. To apply frontloading of DES, and other VM tools, the specifications need to be of improved quality to enable validation of a model.

Quality assurance is one of the most important themes of software engineering, and consists of verification and validation. A definition and declaration of verification and validation in the context of DES and manufacturing systems is provided below with reference to Rhorer [2000].

**Verification** is the process of comparing the conceptual model with the computer model. The conceptual model is an intermediate point between the actual system and the computer model. It may take the form of a simulation specification document, a system flow diagram, or even a sketch on the back of an envelope. The model builder is usually the one performing verification, although others should be involved in the process. Some in the simulation industry equate verification to “debugging”, however it is much more than that. Verification includes many techniques from model “walk throughs” to sensitivity analysis. Animation is important in the verification process as it provides a visual trace of events as they happen.

**Validation** is the process of determining whether the model reflects reality. When modelling existing systems where good data exists, the process of validation can be quite straightforward. However, when the system does not exist, validation becomes more complicated. This is where graphics play an important role. Typically, validation
requires many individuals, each with a particular domain of knowledge and experience. Animation becomes instrumental when communicating how the proposed system will work. The audience is varied, but all must be brought to a common level of understanding before model validity can be determined. Animation, combined with sound statistical analysis, is an unmatched approach to evaluating how good a model really is.

It can be established that verification of a simulation model refers to further activities than just the finished model and simulation results. Verifications imply a continuous check for relevant specifications and data implemented in the model during the entire modelling process. This requires information collection from a number of collaborators, given by documented specification, interviews and questions asked by the simulation expert. In order to build better models and achieve efficient implementation of simulation results the communication between team members needs to be univocal. Visual references in the simulation package provide a medium for better understanding in the dialogue within collaborators. This is in contrast to modelling of existing systems, where good data exists and the process of verification and validation can be quite straightforward [Rhorer, 2000].

As mention by Rhorer above, a conceptual model may take the form of a simulation specification document, system flow diagram, or even a simple sketch. This is a matter of how to express and communicate an idea, and implements its characteristics in a simulation model. Since this is a key factor for building quality models in early development stages, the issue of modelling is given more attention in chapter 3.4, Models or prototypes.

3.4 Models or prototypes

3.4.1 Why?

This chapter discusses models and prototypes in order to clarify the conception of prototyping and prototypes in more detail, and describe how this can be used in conjunction with the modelling of a manufacturing system. It is of particular interest in relation to references to previous chapters about Virtual Tools and Discrete Event Simulation.

In daily talk, we define a prototype as "an approximation of the product along one or more dimensions of interest" [Schrage, 1993], and when we think about a prototype, it is usually used to verify the final design of physical products by a physical model. Then prototyping refers to the design of the prototype and how it is used in the development process for problem analyses and evaluations. However, the conception and meaning of the term "prototype" varies between cultures and the language used to describe them. In organisations with strong technical and engineering culture, only the working model is called "the prototype", everything else is called a model or a mock-up. In more design-intensive organisations every product model built, no matter how rough, is called a prototype. No matter what it is called, the crucial thing is the use of prototyping and how the prototype is integrated in the development process, together with a common language shared between every involved participant of a development project. [Schrage, 1993]

3.4.2 Dimension of Prototypes

In the previous section, discussing structured development, prototypes are not explicitly mentioned in conjunction with some stage or development in any model. Prototyping is instead clarified as being an activity that occurs at any time during the development process when there is a need for analyses supported by a model.
According to Ulrich and Eppinger [1995], prototypes are used for:

- **Learning**: “Will it work?”, “How well does it meet the customers’ needs?”
- **Communication**: To enrich communication with top management, vendors, partners, extended team members, customers and sources of financing
- **Integration**: To ensure that components and subsystems work together in the product or system.
- **Milestones**: In later stages to show that the desired level of functionality has been achieved.

In a wider definition, any entity that exhibits some aspect of the product that is of interest to the development team can be viewed as a prototype. This definition is purposely broad and includes prototypes ranging from concept sketches to fully functional artefacts.

According to Ulrich and Eppinger [1995], prototypes can be usefully classified along two dimensions as illustrated in Figure 8. The first dimension is the degree to which a prototype is physical as opposed to analytical.

- **Physical prototypes** are tangible artefacts created to approximate the product. Aspects of the product of interest to the development team are actually built for testing and experimentation. Examples of physical prototypes include models, which look and feel like the product, proof-of-concept prototypes used to test an idea quickly, and experimental hardware used to validate the functionality of a product.

- **Analytical prototypes** represent the product in a non-tangible, usually mathematical, manner. Interesting aspects of the product are analysed, rather than built. Examples of analytical prototypes include computer simulations, systems of equations encoded within a spreadsheet, and computer models of three-dimensional geometry.

The second dimension is the degree to which a prototype is comprehensive as opposed to focused.

- **Comprehensive prototypes** implement most, if not all, of the attributes of a product. A comprehensive prototype corresponds closely to the everyday use of the word prototype, in that it is a full-scale, fully operational version of the product.

- **Focused prototypes** implement one, or a few, of the attributes of a product. Examples of focused prototypes include foam models to explore the form of a product, and wire-wrapped circuit boards to investigate the electronic performance of a product design.

A common practice is to use two or more focused prototypes together to investigate the overall performance of a product. One of these prototypes is often a “looks like” prototype, and the other is a “works like” prototype. By building two separate focused prototypes, the team may be able to answer its questions much earlier than if it had to create one comprehensive prototype.
Figure 8 Classification of prototypes, Ulrich and Eppinger [1995]

There is no distinct answer to the question of when and how to use prototypes, even if it is a crucial activity in the design work. The use of prototypes is further discussed in the article “Cultures of prototyping”, by Schrage [1993]. More than simply models, prototypes are by Schrage [1993] analysed to be indicators of a company's culture and its ability to innovate. He clarifies the differences between specification-driven and prototype-driven organisations, comments on the purposes of prototypes, and evaluates how the media, language, scheduling, and politics of prototypes affect the development process for better or for worse.

In the organisation that is driven by specifications, the innovative process is used to come up with a finished prototype. This is in contrast to the prototype-driven organisation, where rougher prototypes are frequently used to drive and stimulate the innovation process through its stages of determining specifications.

In the Prototype Culture Diagnostic Matrix, prototyping is given dimensions such as Informal vs. Formal, Internal vs. External, Opportunity vs. Risk Management, illustrated in Figure 9. This matrix offers a diagnostic for organisations that want to access their prototyping cultures. Moreover, this article by Schrage discusses the vocabulary used to describe a prototype. It is clear that different prototyping cultures develop their own language and vocabularies. “Trying to understand the prototyping culture without learning the language is like attempting to understand accounting without using numbers”. Then, the media from which the prototype is created provides alternatives to express a response to questions asked. Prototyping in clay or wood was limited compared to modern foam material that enables easy shaping and surface finish [Schrage, 1993].
This article by Schrage [1993] argues that strong prototyping cultures produce strong products. While the great ethnographies of prototyping cultures have not yet been written, it is apparent that fundamental differences in corporate prototyping cultures lead to qualitatively and quantitatively different products. Clearly, prototypes cannot simply be divorced from the culture that creates them. A crucial conclusion from this article is to remember that a prototyping culture, like any complex culture, is not the product of one or two ingredients, but emerges from the dynamic interaction of these ingredients. Prototypes are the palpable products of those interactions.

3.4.3 Visualisation in DES

It can be questioned whether a DES model is value added by visualisation. To provide some more substantial references to this matter, the following reasoning should be seen in close relation to the previous section about prototypes and prototyping.

The development of computer graphics has accelerated considerably in the last few years in a number of application areas of industrial use. This can be seen in product design by the creation of CAD objects in various contexts as well in conjunction with manufacturing system design and simulation. The improvements of computer graphics are also reflected in the labour market, where Scientific Visualisation is now frequently used to define work tasks in various areas. Examples can be found in mathematics and meteorology, fields where visualisation has become fundamental for better understanding of functions and analyses of a complex nature.

A driving force in the development of computer graphics and related technology is computer games, where requirements of powerful graphical adapters are of vital importance for the visualisation of the virtual world of the game. The strong demand for powerful graphics adapters has resulted in prices being reduced radically, which makes the power of visualisation accessible to a wider extension of users. Moreover, game technology often implies an interaction with the game process, which is often realised by ActiveX, a Microsoft standard. ActiveX is defined in Windows2000 help files as “A set of technologies that allows software components to interact with one another in a networked environment, regardless of the language in which the components were created”. Industrial application of ActiveX has also become increasingly frequent, enabling interaction with a process that is visually represented. In some applications, such as Virtual Surgery and Flight Simulators, the real-time interaction with the model world is an unconditional requirement. In other applications time scaling is of importance, where the dynamics of a slow process can be speeded up and observed almost instantaneously. Examples of this are simulation of various manufacturing
strategies of a week, a month or more, which can be simulated and examined in a few minutes.

The interplay between the observer and the simulation process is present to a varying extent in most DES software today, and different degrees of visualisation have had a considerable influence on the conditions for interaction with the simulation model. Visualisation can be done by simple icon graphics in 2D with some example icons showing 3D perspectives, or in 3D worlds of the entire manufacturing system. In some cases some of these more advanced 3D DES systems also represent a true-to-scale representation and collision detection of moving objects. Both material that is moving and statically represented objects, such as machine equipment, can be designed in a 3D CAD system and imported in the DES model. This enables graphical detailing of equipment and material that can be of crucial importance for a proper design of the DES model. Moreover, user interaction of an ongoing simulation is possible by application of the Active X interface, which can be observed visually as a consequence reaction in the running simulation process.

The distinction between visualisation and animation should however be noticed. Thus, animation refers to a predetermined experience that cannot be changed by the user, as clarified earlier in chapter 3.2.1 with reference to Banerjee and Zetu [2001]. Animation refers to a non-interactive example of visualisation, just showing a scene where the interaction is limited to start, stop and pause. Visualisation can be represented in many alternative ways, and certainly by animation of a simulation process. The difference is when the user is able to control or interact with the visual interface; then it is no longer animation.

The simplest way of interacting with an object or simulation process is by turning, rotating, zooming and navigating in the model. In this way the simulation process can be run and examined in various perspectives with focus on a specific problem area. The potential for sharing experiences from a simulation-run among colleagues, or interest parties not initiated in simulation techniques, is obvious. A more qualified example of interaction is visual interactive simulation, which enables the user of the model to actively participate in the simulation. Harrell & Tumay [1995] consider this trend of visual interactive simulation to be useful for rough experiments and conceptualisation, but limited since statistical changes are hard to match interactive variables. Critical voices are also raised towards visualisation, pointing out the risk for “drowning” in animation, [See Sadowski (1999) among others.]

The benefit of visualisation in DES should be evaluated in different contexts of the life cycle of a simulation model, which concerns the modelling stage as well as the actual simulation. Moreover, the definition of the simulation problem can also imply using visualisation for enriched communication in design, problem solving and training. Put simply regarding modelling, a simulation model was in its origin just a program code in e.g. Fortran, and simulation produces results presented in a numerical state. A simulation model just consisting of program code is hard to understand for anyone other than the programmer who made the coding. This also implies difficulties in verifying the proper design and validation during the modelling stage, and subsequent interpretation of simulation results. In particular, it can be assumed that visualisation supports the use of DES for systems existing just in the shape of an idea and concept.

A method for reducing the model creation cycle time by the use of CAD objects is presented by Paprotny, I. et.al (1999). Here the focus is on automated material handling systems and a methodology that significantly reduces the effort in creating a model by automatic model creation based on the attributes in CAD objects. Three conditions must be fulfilled in order for the methodology to be applicable. First, a CAD layout of the designed system must exist. Second, the simulation model has to be based on a dimensional accurate representation of the
physical system components. Third, the models created must be similar in logic and general structure so that the same CAD transfer template can be re-used. Visualisation is not specifically mentioned here in other ways than “dimensional accurate representation of the physical system components”, which actually refers to CAD objects that are visual 3D objects.

The reason for locating this subchapter in the context of Models and Prototypes is to illuminate what visualisation in DES actually represents. It could be discussed whether a DES model can be categorised as a prototype or not, if necessary. According to Schrage [1993] the use of models or prototypes is a matter of culture or attitude to using various kinds of prototypes. The use of models and prototypes is seen here as the creative dimension and force in the development process. This is in contrast to organisations whose development work is well structured and systematic, and guided by specifications. In product development, Schrage [1993] found that organisations that used prototypes to a greater extent were more successful and competitive in the market. However, this article was written before virtual prototyping had reached the level it has today, as virtual prototyping has now become obvious to each product designer. As illustrated in Figure 8, Ulrich and Eppinger [1995] classify prototypes in two dimensions, physical as opposed to analytical, and comprehensive as opposed to focused. According to this, a DES model in its basic form, i.e. program code of the discrete event simulation process, represents an analytical model. Nevertheless, adding visualisation to a DES model of a manufacturing system makes it enter the area of comprehensive and analytical models.

Prototyping implies the embodiment of an idea or concept, traditionally realised by a physical model. Today this is realised by computer graphics, and visualisation is achieved by a virtual model, or even a simulation process showing the behaviour of the model in alternative situations. The ability of visual perception refers to one of the strongest human senses. Although we sometimes resist it, no one can deny that visualisation is a powerful mode of communication. Because simulation is often used in order to better understand complex systems, it requires the most efficient method of information processing. Rhorer (2000) states that visualisation in simulation utilises the mind’s ability to process large amounts of information quickly. According to Rhorer visualisation is the best means of helping the simulation processing in the areas below. The area of simulation where graphics are most important is model verification and validation.

- Verification and Validation
- Understanding of results
- Communication of results
- Getting buy-in from non-believers
- Achieving credibility for the simulation

Moreover, Robinson [1997] states that both model logic and real-world behaviour can be verified by looking at the model. A similarity can be found in the context of PC games, such as the game SimCity™, where a Teacher’s Guide is also available for using the simulation model pedagogically, in order to provide a better understanding of, for example, town planning. As the size and complexity of systems increases, visualisation in DES is no longer a luxury but a necessity for proper analysis to support good decisions. Moreover visualisation can be a key to efficient communication in a cross-functional organisation, a pedagogical support in the training process. The interplay between simulation and visualisation is obviously a powerful combination, if used correctly.
3.5 Application of VM in the development process

3.5.1 Problem definition in the design process

Accuracy in defining a problem during the early stages of the development process is emphasised by Norell [1992]. The effort to discover each factor influences the design and the development process is a crucial activity for achieving a convergent development process and an optimal solution. The opposite is the divergent development process, where problems and specifications have a tendency to be underestimated or neglected during the early stages of problem definition. In a divergent development process a major effort has to be used for adaptation or error correction, which is a very costly business. A divergent development process is more to categories as chaotic.

![Diagram of Convergent vs. Divergent development process](image)

*Figure 10 Convergent vs. Divergent development process [Norell, 1992]*

Conversely, there is a natural explanation for the tendency to underestimate or neglect the specification of problems, problems that have a tendency to grow and cause larger problems at the end of the project. One reason for this is simply that it is complicated to overview and manage a large complex project. There are reasons for finding tools and methodologies supporting the process to converge [Norell 1992]. It should be mentioned that these conclusions by Norell [1992] do not consider the implementation of the virtual environment that is offered in engineering today. This emphasises the importance of a qualified pre-study and structured approach to the design problem, regardless of whether virtual support is used or not. It can be assumed that the virtual environment likewise supports the knowledge of the planned development process by digital representation and simulation.

3.5.2 Improved knowledge by virtual support

The definition "early development stage" used frequently in this thesis, emphasises the period of development when the planned system just exists as one or more concepts, represented by specifications and as a model of some kind. This is in contrast to developing or reengineering a real physical manufacturing system with documented data.

In order to understand and manage a project without physical references, a virtual development arena can be of great support in achieving a convergent development process. A similarity can be seen in product development where simulation and digital prototyping based on a CAD model enables an analysis of features for a product existing only as digital model. This is a domain where software application in the area of modelling and simulation has achieved a more mature stage compared to VM. The work method for using modelling and simulation in the product design process is obvious. In this way knowledge about the product
is obtained already at the ideas stage when there is design freedom, and changes can easily be made at reasonable cost by changing the model. In the case of product development, this work method results in shortened lead-times and better quality at a lower cost. In addition, the improved knowledge will help to avoid changes after the final design, which is costly and delays the start up of the manufacturing process that generates new income.

This potential for using virtual technologies within the early stages of product development is pointed out by Krause, Heimann and Kind [2001], among others. As illustrated in Figure 11 below, the knowledge curve moves towards increased knowledge earlier in the development process by the use of virtual technologies, together with the use of companies’ expert knowledge and evaluation methodologies, as illustrated in the figure [Krause et al., 2001].

![Figure 11 Increase of product knowledge [Krause et al., 2001]](image)

In analogy with the product example above, the development process of new manufacturing systems should be greatly influenced by VM applications. This need for changes is characterised by Klingstam [2001] as frontloading, as illustrated in Figure 12. The figure illustrates how Virtual Manufacturing is put in a new position in the development process, where it is not only used to verify solutions, but also for design support and analysis of alternative solutions. This gives the industrial engineers new scope for improved quality in their work. The potential to test and verify ideas, handle complexity and communicate the design among team members, are some of the features that come with these new rapidly developing digital technologies within the domain of VM.
Simulation of non-existing manufacturing systems is less reliable than simulation based on data and specifications from an existing system with historical data, knowledge of equipment and manufacturing strategies, etc. In some respects this is in contrast to traditional simulation theories and methodologies, with models including statistical functions and analyses. Even if an incomplete specification is held to make results from the simulation in the early stages unreliable and hypothetical, modelling and simulation should still provide improved knowledge about the system under development, as illustrated in Figure 11. However, efficient integration of a VM environment requires executives, project management etc with insight and competence in this subject, according to Andreou et al [1999], and many others.

### 3.5.3 The future of VM

The most elementary example of virtual representation is a 3D CAD model of a product that can be examined on a computer screen by rotation and navigation. The extreme is the fully integrated VR manufacturing system, where the observer can interact and examine an object or situation as illustrated in Figure 13. Here the person is equipped with glasses and gloves that are linked to the model action in real-time. Parts in the factory can then be seen travelling through their manufacturing process throughout the day. The time can be adjusted to examine part flow in the different scenarios loaded and compared to the system. [Banerjee, Zetu [2001].]
The domain of virtual manufacturing environments stands for a complex variety of applications, which appear in table 1, chapter 3.2.4, of VM application at Volvo. These examples are just a hint of what is offered by commercial vendors of software, within the field of virtual environment. Most references of virtual applications are found in the context of large industries, automotive industries being one of the frontiers. On the other hand modelling of mid-sized manufacturing operations is seen as a future application area for DES [Banks. 2000], which also implies application of VR support of some kind.

Applications of virtual solutions are frequently represented in product design, and work methodologies can therefore be seen as a foreground. Lining up ideas and concepts in a CAD system is an obvious activity here, already at the idea stage, i.e. the early stage. The CAD model also constitutes the core for other applications representing various degrees of VR. Three premium advantages are pointed out by Östman [1998] in a broad study on VR implementations in the United States: shorter development lead times, decreased costs, and increased quality [Östman, 1998].

3.6 Organisational aspects of a development team

3.6.1 Integration

A development process is a dynamic activity based on human creativity and methodology, supported by various kinds of support and computer tools. For success in product development the following key features are identified by Syon and Menon [1994].

- Multi-disciplinary teams
- Cross-disciplinary communication and co-ordination
- Quality management methods
- Computer simulation of products and processes
- Integration of databases, application tools and user interfaces
- Education and training programmes for employees at all levels
- Attitude from employees towards ownership of processes
- Commitment to continuous improvement

It is not product development, but manufacturing development that is in focus in this research. Nevertheless a development process must be managed so that cross-functional effects will infiltrate the workflow. Moreover, integration must be present in a number of ways. To mention a few examples, there is a need for integration of the practical manufacturing knowledge of workers and technicians, engineering specialities and the manager’s overall perspective.

The need for integration has been pointed out largely in literature dealing with product development. It is crucial to work for integration within a numbers of disciplines, ranging from psychology to technology. According to Forslin [1992], integration can be classified as follows:

- Vertical: Decentralising and meaningful work
- Horizontal: Work extension, job rotation, flow groups
- Functional: Closeness between functional units
- Lateral: Between customer and supplier, between competitors
Spatial  
Between geographically separated units

Temporal  
With increased level of simultaneity and parallel processes

Normative  
Shared values and visions, permeating ideas and organisation culture

Financial  
Involvement in profits, result-related payment

Technical  
Common use of information, multi-functional equipment, group ware, and more effective communication media

Social  
Looser boundaries between white- and blue-collar workers

All these integration aspects should be more or less present in successful organisations, as they can have a positive effect on all the activities within the company or project, and the development process in particular. In their book "Integrated Product Development", Andreasen and Hein [1987] emphasise the importance for manufacturing firms to come together in order to carry out the development of a product as an integrated activity as far as possible. Integrated Product Development aims to answer the questions: Which integration mechanisms lead to effective co-ordination? and In which situations is there an overlap of new product development activities? [Andreasen and Hein, 1987].

However, while a number of wood-industrial activities are related to SME’s conditions located in rural regions, the cross-functional work organisation can not always be easily achieved. It requires for example accessible specialist competence, which can be hard to find locally, or that large geographical distances are overcome by other arrangements. Moreover, a cross-functional development team requires that its financial recourses are not accessible for a SME. To overcome some of these problems Distributed Engineering has become a possibility for concurrent activities by co-ordinating engineering work throughout the Internet. This means that an advanced and complex development process of a manufacturing system in a rural region can be accessed by a cross-functional team distributed globally; team members can be located anywhere in the world as well as in the rural forest regions of the inland of Sweden.

To sum up, an organisation intending to launch an industrial development project can utilise a modern VM environment and its facilities for distributed engineering to achieve a cross-functional team that can co-operate independent of geographical distances. This implies that integration in the development process has to be fulfilled in a number of respects, under conditions relevant for a geographically distributed organisation.

3.6.2 Distributed engineering

Distributed engineering provides engineering disciplines with a number of alternatives to organise and carry out an assignment without having all team members present in one location. Advances in broadband networks and Internet communications are a key factor to enable distributed work procedures. Moreover most of today’s software applications are adapted to support a tele-collaborative virtual environment in some matter, from easy access to WWW and mail, to more advanced systems for interactivity or distance utilisation of powerful computer resources in various types of analyses or simulations. In other words, distributed engineering implies both access to various computer resources and the ability to co-operate in a virtual environment [Johanesson and Kempinsky, 2001].

As described earlier, wood industries are often located in less industrialised regions close to raw material sources, a situation that does not attract young engineers to a career in the industry. Technology transfer and industrial development in less industrialised parts of a
region imply other conditions than in industrialised regions; this is a standard scenario for a number of wood manufacturing industries, which is similar to our industrial case. Technology development projects in these regions often depend on the expertise of consultants who visit for short periods during the development phase, and then finally they leave, taking their knowledge with them.

New conditions are created by the extensive development of Internet access and software applications provided with web interface. The web presents an opportunity to achieve a distributed design framework supporting multi-disciplinary, multi-organisational collaborative design and analysis activities. The potential for deploying online, reusable parts libraries for virtual prototyping and design analysis exists [Wilsey, 1999]. This means in particular that today’s less industrialised regions can consider the problem from another perspective as a result of the new dimension of web communication. Today communications embrace a number of dimensions, such as 3D graphics, interaction through models of various kinds, and databases, just to mention a few examples. Altogether, this dimension of digital information allows communication and co-operation in work worldwide.

Most commonly these applications are found in product development where much of the work is based on CAD models and integrated applications for analyses. Information is then shared among involved project members wherever they are located, in rural regions or any place around the world. Distance co-operative work is usually managed by some variant of a Product Data Management system (PDM). A previous section about standardisation of information in chapter 3.2.3 discusses the importance of standardised information.

Visualisation is always present in virtual applications. To enable visualisation over Internet, implementations of Virtual Reality Modelling Language (VRML) have been used, and VRML has also become an ISO standard. By converting a model into VRML format (1, 2 or 3) it can be shared among team members as a 3D mode, and examined in an Internet browser with a “plug-in” such as COSMO by SGI and acquired subsequently by Computer Associates, or Cortona by ParallelGraphics.

3.7 Wood manufacturing supported by VM

3.7.1 Why bother about the wood industry?

As the description in the introduction tells, forest industries and the sector of wood manufacturing are of significant importance to the trade surplus of Sweden. This sector represents the largest net income in the Swedish industrial trade balance. It is also based upon a renewable raw material source, producing more than is used in the forest industries sector. The Swedish sawmill industry is today represented by a high-tech process industry with major exports of sawn products. Value-added wood processing industries, working with sawn raw material for manufacturing furniture, carpentry or other more sophisticated wood products, is on the other hand not as well developed. In particular this is the situation in the less industrialised regions of northern Sweden, where a large part of the raw material supply, as well as a number of modern sawmills, are located. The location of wood industries is also related to a massive transportation procedure, which is costly and has negative environmental effects, in that raw material is sent to industries often located a long distance from the raw material source. Therefore the development of wood manufacturing industries close to the raw material source is seen by the inland municipalities as an important factor, both for the improved utilisation of raw material, and also with regard to arguments concerning labour market policy. The qualifications of these companies in modern manufacturing technologies, such as mechanisation and automation used in flexible manufacturing strategies of various kinds, is not very often implemented. Another disadvantage these industries have to manage
is large geographical distances between industries with potential for co-operation. It can be summarised that wood manufacturing is an industry that does not have the image of being technology-intensive. Among many young engineers, wood manufacturing and manufacturing industries in general represent conservatism and low-tech, conditions that do not attract engineers to a career in the industry. Wood manufacturing is also an industry with a relatively high age structure among its personnel, as well as poor experience of new technology such as computer-supported work.

Consequences in the management of development activities in industry are obvious when executives have low insight into computer tools and the organisation needed for this kind of work, as pointed out earlier in this thesis with reference to Forslin [1992], and by Forslin’s references already in the 80s. Moreover a company’s ability to attract qualified competence in various domains of virtual applications, is defined as a key factor in competitive strength [Johannesson and Kempinsky, 2001]. This also includes applications for distributed engineering that could be of crucial importance to those industries that are located in rural regions.

From another perspective, a branch of industry is often designated by the term technology, for instance mining technology or agricultural technology. By definition, the term “technology” means the symbiosis between a technical system and a social system, Forslin [1992]. Thus we can observe technical development within social systems with particular needs, such as in coastal regions with their development of fishing technology, or in our case, industries located in forest regions and their development of wood technology. So, when we are looking at industries processing wood there are some unique characteristics, as well as a great deal in common with manufacturing systems in general. The question is what we have to consider as unique factors in the wood industries, both advantages and disadvantages, when it comes to utilising the support by VM.

To satisfy the need for qualified competence in the manufacturing industry the efficient use of computer-supported technical work provides new possibilities. This is a matter of distributed engineering, enabling worldwide co-operation with specialists, customers and suppliers involved in the development of products and production throughout web communication. Change in this direction comes with by application by VM and might changes these industries competitive strength as well as its attraction to secure competence among young engineers. Development of new manufacturing systems is a priority in these rural forest regions, and the potential for support by VM is obvious for anyone who is initiated, but is it realisable?

3.7.2 Digital modelling and simulation in wood industries

As pointed out in basic DES literature the use of DES in the early stages is considered to be difficult because of an incomplete specification that makes results from the simulation unreliable. An additional uncertainty to be considered is the fact that wood processing implies even further incomplete specifications because of the unknown result of decomposition from sawn boards into components.

Wood is a biological material with wide variability regarding both its mechanical and aesthetic properties. This influences both the yield of the raw material and the quality of the manufactured components. The quality of the raw material also influences the manufacturing process, material handling as well as machining. Thus, if there are defects in the material, e.g. knots or rot, the machine process could be interrupted or disturbed. This implies discontinuities in the process that are hard to estimate in advance. Wood also represents hygroscopic characteristics, causing shrinking and swelling as a function of the humidity, which results in various forms depending on the piece of wood. Wood also has its fibre
structure, which gives the material three-dimensional mechanical properties, and the fibre structure has to be considered when machining. Compared with other industrial processes based upon materials such as steel, polymers etc., the number of uncontrollable factors increases in the processing of wood due to its variation in properties. The characteristics of the wood material, and their influence on the manufacturing process, complicate the process of modelling and simulation radically. As mentioned earlier, these conditions related to the properties of wood complicate the application of DES in wood industries.

Depending on the problem in focus for modelling and simulation, the level of detailing has to be chosen corresponding to the complexity of the actual problem. For example, in the case of conceptual evaluation of manufacturing lines, the dynamics of material flow might be complex enough to understand, even without considering the wood characteristics in detail in the simulation model. Moreover, if a representation of wood characteristics is required in the model, the level of detailing can be implemented by degrees. The real problem is how to know and define wood properties and yield data, often expressed in subjective values, and how it influences the manufacturing process in a consistent form, irrespective of the use of DES. Necessary inputs to a process simulation model typically include processing rate data, downtime data, operator availability data, transportation and conveyor speeds and distances, and product yield data. For wood manufacturing, the structure of in-data is more complex. Product yield data for a wood manufacturing industry consists of information on the number and size of parts produced at each machining operation (e.g. crosscut saws and ripsaws). Individual machine yields vary considerably depending on the product (cutting bill) and the raw material (lumber size and grade). For example, what is your lumber length and width distribution within each lumber grade? What is your lumber grade mix? How long does it take to process each board/strip/cutting through your mill’s planer? Crosscut saw? Moulder? Rip saw? How are these processing rates affected by lumber grade? How are they affected by lumber length? By lumber width? By lumber thickness? By drying degrade?

Even the most data-rich companies do not have the type of data required to build an accurate simulation model. In order to collect data it takes a lot of time, depending on what the focus of the model is and how precise the model needs to be. For example to attain the yield data, it is usually generated by running cut-up simulations of the crosscutting and ripping operations. Furthermore, Araman and Wiedenbeck (1994) emphasise that a good insight into these unique conditions of wood manufacturing is required in order to build a reliable simulation model, i.e. a synthesis of actual conditions and requirements into a simulation model. In this context, an investigation of simulation usage among U.S. furniture and cabinet industries was carried out by Araman and Wiedenbeck (1994). Potential applications of process simulation that were found are as follows:

[1] To investigate the impact of lumber length on productivity and profitability (see also [3] and [4]).

[2] To investigate the impact of lumber grade sorting on productivity and profitability

[3] To investigate the impact of outside dimension purchases on order and machine scheduling.

[4] To investigate the impact of lumber length sorting on productivity and profitability.


[6] To investigate the impact of establishing machining cells for processing part families

To investigate the production and labour impact of replacing manual chop saws with automated chop saws.

To investigate the impact of Just-In-Time-type demands on machining operations and costs.

To investigate the production impact of finger jointing.

Moreover, Kline Wiedenbeck, Araman (1992) and Araman and Wiedenbeck (1994) found a noticeable usage if visualisation by animated material flow showing the dynamics in the material flow in lines and queues. An example of the actual model used to illustrate operational states and queues is shown in Figure 14. At that time (1992) visualisation features in DES were limited to show process states by “idle”, “busy” or “down” along with symbols of material in conveyors or queues.

![Figure 14 Snapshot of the simulation/animation model of the roughmill at time = 253 minutes](Source: Forest Products Journal Vol. 42, No.2)

Providing a dynamic visual representation of the system was by this simple visualisation found to be an efficient method of finding a problem as well as finding the cause of the problem. In terms of simulation model development, the animation feature was also found to significantly reduce the amount of time it takes to verify and validate a simulation model. In communication and documentation, it was found to be much easier for managers to understand familiar pictures than tabulated values and graphs. Therefore, providing a real-time visual representation of the system enables those not familiar with the interpretation of traditional simulation output to feel more confident and understand the results [Kline Wiedenbeck, Araman, 1992]. However visualisation is still a matter for deliberation, while its development has been extremely fast in this area [Sadowski, 1999] [Rohrer, 2000]. Nevertheless, it can be assumed that visualisation in this context provides a more qualitative dialogue between those who are initiated in wood manufacturing, and those who are specialists in simulation.
3.7.3 Wood machine design

Wood is a soft material generating low cutting forces that are easy to manage in a machine design compared with the design of steel processing equipment. Unique wood processing equipment is thus relatively easy to design and build. Therefore, it can be supposed that freedom and possibilities in machine design offered to both the mechanical engineer and the industrial engineer, is a potential for innovative development of manufacturing systems. This is a matter of problem solving and design freedom to develop unique equipment for actual needs. New design of wood machinery can extensively also be based upon modular components such as cutter heads, handling and feeding mechanisms, provided by industrial vendors. These conditions make design, redesign and adaptation of machine equipment less costly and more innovative in character, compared with similar work with more heavy equipment in other industries.

3.7.4 Machine vendors vs. Wood Industries

It is machine suppliers in close collaboration with the wood industry who usually develop special machine equipment and even entire process lines as "turn-key" projects. When a project has reached installation and start up, there are always major or minor adjustments that have to be made. Some adjustments might depend on technical trouble that is hard to anticipate; others might be caused by misunderstanding or incorrect information. This relation and dialogue between the wood manufacturing industries and vendors of industrial equipment is generally a critical point for verification between parties. Since competence in industrial technology within the wood manufacturing industries does not correspond to industrial vendors in daily designing work, misinterpretation in the dialogue occurs in the wood industry and all other branches. In particular this is related to the implementation of new technology, such as automation, robotics and visual scanning techniques, where implementation requires a system approach to avoid sub-optimisation. In this case the benefit in terms of improvements in the overall quality of the project by the use of VM serves both parts through a dialogue based on a visual DES model.

VM provides machine vendors and wood industries with a new development arena. In this way the dialogue can be improved between executives, financiers, workers, or other specialists involved in the design process such as PLC (Programmable Logical Control) programmers or ergonomists designing a unique workplace.

3.7.5 Material handling

Material handling is more or less done in considerable proportions between each process operation in wood manufacturing. It consists of feeding devices for longitudinal and cross-direction movement, and in particular up and down stacking in staple or buffers that are also moved into other process lines or storages. Dominating processes are carried out in the longitudinal direction by cutting operations such as planing, surfacing, profiling, or splitting, during simultaneous feeding of the object at a relatively high speed. On the other hand, other processes, usually oriented across the object and across the grain, such as cross-cutting, drilling, or milling, are not done so fast in relation to feeding per piece. Sorting of objects by their variation in quality and aesthetical properties is another material operation that is particular for wood processing, and has its own subchapter in 3.7.6 below.

According to Kline and Araman (1990) in a discussion of the wood furniture industry, over 95 per cent of the time is spent on non-value adding activities such as handling, waiting, and storage. This means that a furniture part can spend less than 5 per cent of its time undergoing processes that increase its value, such as machining, assembly, and finishing. To address
some of these problems, most research has focused primarily on developing better processing equipment technology. Computer vision, robotics, and computer-integrated manufacturing are examples of recent technological innovations, which have been successful in other manufacturing industries such as the automotive industry. Such technologies were proposed for modernising furniture manufacturing facilities already in early 90s by Kline and Araman [1990].

3.7.6 Automation and sorting by scanning technologies

Today development of new technologies for visual scanning enables automatic sorting and efficient material handling by scanning of geometrical and surface properties. Traditionally this has been done manually, and has been costly and time-consuming. Therefore, implementation of scanning technologies is a powerful contribution to efficient wood manufacturing. Moreover, these scanning technologies are integrated in an automatic material handling system.

As mentioned in the previous chapter automation and visual scanning technologies are designated to be of crucial potential for managing a situation of considerable material handling in wood manufacturing. Implementation of such technologies is expensive and a difficult task that requires analyses of the influence each process has on the logistics of the entire system. For example both scanning and automation are concerned with material flowing controls that are related match manufacturing strategies of the entire manufacture system. To avoid incorrect analyses that may cause sub-optimisations in the material flow, an understanding of the logistics of the complete system is crucial. Such system analyse can be realized by DES.
4 THE INDUSTRIAL REFERENCE CASE

The industrial development project used as a reference is presented here in detail, together with an outline of the study and how it was carried out. The study focuses on two subjects: the actual development process, and the potential for the application of computer support by DES. Results from these two subjects are then presented in chapters five and six.

4.1 A unique situation

In order to build up knowledge concerning the research question addressed in this thesis, an ongoing industrial project has served as a reference of industrial realism. The project considers the development of an 11,000 square metre plant, which is highly automated for the manufacture of parquet and laminated wood flooring. It constitutes an investment of more than USD10,000,000 in the inland forest region of northern Sweden.

This development project provides a unique source of substantial industrial realism, used here with reference to academic theories in various fields. The aim is thus to achieve a synthesis between industrial realism and academic theories, as illustrated in Figure 3, page 9.

Previous descriptions of wood manufacturing industries are in a number of cases exemplified by conditions present in this development project. It is a pure wood manufacturing industry, developed by people with their knowledge base in this industrial sector, and it is located in a rural region of northern Sweden.

However, one condition should be pointed out already about this actual project. It is not carried out within a permanent organisation, e.g. within a company or a large corporation. This is more a result of the commitment of a few people with a strong entrepreneurial will and limited financial resources to carry out such an extensive project.

4.2 Structure of the study

In this industrial project, two fields are particularly interesting to study: first how the development process was carried out, second the potential for use of DES in the development process.

The industrial development process started in 1997 by exploiting the idea of the new plant. This part of the study is illustrated in Figure 15, as “Studies of the industrial development project”. This refers to the time when collecting material for this study started in quite an informal manner. Observation of the development process was then planned to continue until 2001 when the start up and trimming of the plant was planned.

The study constitutes a survey of the industrial development process that is based on conventional methods with no extensive computer support. It is managed by experienced people from the industry, within a very small group of individuals in a flexible organisation. The purpose of the survey is to analyse the industrial development process, in order to find a structure of ongoing processes and stages reached. Thus chapter 5, The Conventional Development Process, constitutes a crucial reference to chapter 6, Computer-Aided Development, providing guidelines for a development process and showing where computer support can be integrated into the process.

This second part of the case study, focusing on computer-aided development by the use of DES, was carried out in a separate simulation project. This is clarified in Figure 15, illustrating how the “Simulation” project was established separately from industrial
development activities. The design of the manufacturing concept was assumed to be fulfilled and the main purpose was to evaluate the original specifications of the plant by DES. The ability of the DES tool to model and simulate a wood manufacturing process was also considered in the study. A future plan discussed, was to evaluate the DES model against the ongoing production scheduled to the end of 2000 or in 2001, illustrated by "Second evaluation" in Figure 15.

Figure 15 Structure of the study.

Besides the academic purpose of this study, outlined previously, the industrial group had an interest in the simulation analysis of the new manufacturing concept. This can be described as a final check on output capacity and risk of bottlenecks in the material flow to avoid major design errors in the actual layout. A simulation model that provided a detailed 3D visualisation and animated movies was also requested by the industrial group.
5 THE CONVENTIONAL DEVELOPMENT PROCESS

This part of the thesis considers the study of the industrial development process of the new plant. This development process is categorised as conventional in the sense that no computer support was used. In other words, these are the conditions, the context, in which DES or other VM tools have to be implemented.

5.1 The organisation of the development team

As mentioned above, the industrial development process originated in 1997 by exploiting the idea of the new plant. This refers to the time when collecting material for this study started in a rather informal manner, mainly as a result of a casual dialogue with the person who is the entrepreneur and inspirer of the project.

This industrial project was carried out under conditions that are a reality in rural regions, such as lack of certain competences and geographical distance to colleagues and other companies. Despite these restrictive conditions this project was nevertheless one of the largest independent projects to be carried out in the region in question, the county of Jämtland, which is located in the north of Sweden. From the start, the development process was carried out by the entrepreneur behind the complete project. In some aspects it can be described as a “one-man show” carried out in an informal network of co-workers supporting in various competence areas.

Therefore it is not obvious to compare this development project with one in a company that has a fixed organisation and other resources suited to development work in general. This is more a question of an informal organisation by the entrepreneur with limited financial resources and the ability to solve whatever kind of problems that had to be solved, e.g. product and markets, manufacturing technology, finance, etc.

The network of supporting collaborators in various competence areas varied over time. The following list of technical competence shows the most distinct work roles involved in the development of the manufacturing system over the entire development period:

- The entrepreneur: The prime mover and overall coordinator of the project from the start.
- The consultant: The owner of the manufacturing concept, supporting the project as it progressed.
- The mechanical designer: The engineer that made a detailed design of the concept and put together the specifications
- The technician: Involved at the time when the decision was taken to build the plant, working on installation and the start-up of the plant.

This is the main core, or the central functions identified within the project team, whose members were involved in the development and design of the new manufacturing system. A number of further competences not listed here were involved from time to time in the development procedure.

5.2 Development stages and activities

This industrial development process covers quite a long time, from the initiation of the project in 1997, to the status in the autumn of 2001. This period is here presented and structured into stages and activities. The definitions of stages are associated with crucial decisions of design
character, changes in the team over time, and so on. In between certain stages, various development activities occur, mainly related to the design of layout and equipment.

The initial development stage is based on the manufacturing concept provided by the consultant, with a number of similar projects being carried out. Flexibility is a key feature of the concept, designed for manufacturing a combination of flooring and laminated boards. The manufacturing concept and products are presented in greater detail in chapter 6.

Two major activities then went on for a long period:

- The detailed design of plant layout with equipment
- The raising of financing resources to cover the investment.

The detailed design of plant layout with equipment is based on the manufacturing concept provided by the consultant. This implies analyses of capacity, as well as alternative specifications for a flexible manufacturing process in accordance with assumed market demand and other factors. Detailed design was then done for various kinds of equipment, such as conveyors, buffers, “pick-and-place” robots, along with adjustment and reengineering of process equipment that was planned to be purchased. Altogether, these technical issues constitute a crucial and substantial material of specifications and layout, supporting the dialogue with those financing the project and others involved.

In this study, we have not focused on the process of raising financial resources. However, technical specifications of the manufacturing concept and products do constitute a crucial material as a basis for decisions in the dialogue with financial actors such as private investors, banks, the government etc. These specifications, the level of detailing and data provided, were considered to be of excellent quality and were well accepted among the financial actors. According to the judgement of people involved in the project, the specifications were considered to fulfil their function of specifying the plant very well.

The next stage reached was when all financial resources had been raised and all design activities were completed, which marks the decision to build the plant. As a result of this decision, land clearance and groundwork for the factory premises could begin, and six months later the installation of manufacturing equipment could start.

The following stage identified is when manufacturing started on a very small scale in one of five process lines, along with the trimming and adjustment of the equipment. This stage was relatively close to the formal opening of the plant, WOW Flooring AB (Walk On Wood) and further production on a very small scale.
An approach to illustrate this development process is given in Figure 16, showing stages reached and processes in between, as well as interaction between processes.

Figure 16 The development process of the industrial project

It was assumed that the installation of equipment would be identical to the specified layout, which was a decision factor in building the plant as well as initiating the simulation project. However, this was not the case, since redesign and adjustment of equipment continued even after the decision was taken to build the plant, or after what was considered as the design freeze in Figure 16. This is in sharp contrast to how the situation was understood by those who were involved in initiating the simulation project, based on what was held to be the final design. Reasons for changes of the original specifications were partly related to changes made by the industrial team, partly by incompleteness in the original specifications. The incompleteness was particularly discovered in the simulation project, by examining specifications in conjunction with the simulation modelling design. This also forms the conditions in which the simulation project became involved in a number of redesign issues, which is further discussed in the next chapter about the simulation project.

Another factor radically influencing the final design of the layout was the situation which arose in connection with buying used equipment from a shut-down plant in central Europe. This was an upheaval stage when major parts of the layout were redesigned. However, the opportunity that came up to purchase used equipment was a very attractive price situation to exploit, and this could not be disregarded. The simulation project now became further involved in a number of design tasks, along with the updating of the simulation model in connection with the new equipment.

Redesign took place simultaneously with the ongoing installation of equipment and start-up and tuning of each line in order to make it work properly. The simulation project was partly active in supporting redesign processes until the autumn of 1999. Otherwise the new design
was managed by the industrial team, using conventional methods in close connection with installation, step by step.

This structure, which is described and illustrated in Figure 16, is rather simplified compared with the real development process, not planned or structured by any kind of guidelines. It is actually rather complex and hard to structure the process, even afterwards. Nevertheless, the structure presented here provides at least an overview of the context in which the simulation project was carried out.

5.3 Summary of results

The following summary of results comprises conditions that are of vital importance to consider for the implementation of computer support in the conventional development process of a new manufacturing system. Results that are related to the simulation project are discussed and presented in the next chapter.

[I] Specifications of the manufacturing system were a crucial component in the dialogue with financiers in order to raise capital for the total investment. Specifications of the final design of the plant constitute a crucial part of decision-making.

[II] A final design of the layout was not completed at the time when the decision was taken to build the plant; this is in contrast to the previous statement. Design and redesign continued for a long time and were finally carried out simultaneously with the installation of equipment.

[III] Financial resources constitute a restriction during the development process. The possibility of involving further resources, such as competence and computer support, involves additional costs that create a barrier.

[IV] A project team was not organised formally. The development is rather based on entrepreneurial spirit and improvisations, where each situation is managed using the resources available at the moment.

[V] The development process is not guided by any kind of systematic approach; it is rather characterised as an innovative and extemporary way of solving problems, regardless of whether they are of a technical, financial or any other nature.

[VI] This project was carried out in a rural region that in many cases corresponds to the conditions described in the introduction about wood manufacturing industries.
6 COMPUTER-AIDED DEVELOPMENT

The following part of this thesis describes the simulation project in terms of how it was set up and carried out by modelling, and the results it produced by simulation. A presentation of the manufacturing line and a detailed description of the product is also given here.

6.1 Initiation of the simulation project

Based on the assumption of a definitive layout, the simulation project was initiated within this study during the winter of 98/99. The purpose of the project was to work on the initial specification and outputs calculated manually, and then compare this with results from a simulation of the same conditions. There was also an interest in studying to what extent a simulation tool could reproduce conditions of wood manufacturing, with the complexity of variables that is related to the processing of wood. A second step was also discussed for the future when the plant was running, in order to evaluate the simulation model by reference to real manufacturing conditions, as illustrated in Figure 15.

This project idea to analyse the system was presented to the industrial group, who showed a great interest. While the system design had already been decided on, the main idea of the simulation project was to validate the system by analysing output in relation to calculated capacity of the actual design that was chosen. The aim was therefore not to influence or come up with alternative solutions to the actual design, but only to evaluate the accuracy of the layout and its specifications. An additional requirement from the industrial group was that of building a model, which could be used as a graphical presentation of the new plant. By recording animated films made from the simulation model of the planned manufacturing system, presentations could easily be made for customers, agencies, or interested parties of any kind.

An underlying question was to specify how wood manufacturing differs from other kinds of manufacturing industries in the case of using DES. This was of particular interest, since DES is not used so frequently in the wood industry. Altogether, these tasks of the simulation project were accomplished in conditions that refer to early development stages.

6.2 Structuring the simulation project

While the planned manufacturing concept was quite extensive, the design of the simulation model was considered to result in a rather complicated simulation model. None of the individuals in the region had enough experience in DES and therefore some external expert was needed. However, in order to design the project and find suitable DES software, Harrell & Tumay [1995] have a helpful guide in their book “Simulation made easy, a manager’s guide”. One recommendation from this literature is to involve a senior simulation champion, one with the insight into what DES can or cannot do. Furthermore the requirement for good user support from the DES supplier is pointed out as an important key factor for a simulation project. A further question that was focused on concerned the choice of suitable DES software, a question that could be complicated, since there are more than 50 simulations software packages available on the market. On the other hand, the project depended on a simulation expert, who probably had his/her own preferences as regards software.

However, some experiences and wishes concerning the DES were known from earlier simulation projects in wood manufacturing industries, carried out among the academics in the project team. These experiences where found in a simple project done in the type of DES
software that is based on symbolic icon graphics in two dimensions. The definition of icon graphics refers to a simulation model, with or without limited representation of geometrical references, such as those provided by true-to-scale representation of layout and moving objects.

The findings in this small project of wood manufacturing predicted that it is often desirable to simulate conveyers with various lengths and with variable speeds. Moreover handling of different geometrical load types, e.g. boards of various lengths, is a recurrent case of a material flow problem. In particular, spaces in between each board affect the efficiency of the material flow. It was obvious that for some DES software tested, such criteria were a major problem to model, where the user had to define conveyor lengths in terms of multiples of the load lengths. For example, if the load is a 3.5 metre board, then a length of the conveyor has to be a multiple of 3.5 metres (7, 10.5,...). In cases where the conveyor is not a multiple board length, movement times must be calculated by the user. The same problem arises if the user has several load types of different lengths on a conveyor section. Approximations and potential errors were easily introduced in these cases. To handle these cases of various geometrical dimensions, there was a desire to find a DES software that managed true-to-scale objects; both static objects such as the layout, conveyers, and other equipment, and moving objects, such as boards of various lengths.

Further conditions that were considered to be of crucial importance for choosing simulation software were as regards a number of linear robots (x-y-z movement), that interacted with a number of stacking buffers and conveyors. Material handling by conveyors was extensively represented by moving boards longitudinally or cross-directionally, by moving and sliding to stops, or by drag chain conveyors. The portion of material handling in this manufacturing system appeared rather complicated compared with the remaining machine processing. It was obvious that material handling is a dominating procedure throughout the complete manufacturing system, and many similarities to material handling systems in general could be listed. This is a fact that put specific requirements on the DES tool, in order to reproduce real conditions of a wood manufacturing system of the kind in question.

Other requirements identified as crucial factors for choosing the proper DES tool were as follows:

- The price of the software is not a critical point. In relation to the total investment of the plant none of the software costs more than a small fraction. This is the case if the industrial team buy the DES software. On the other hand, other solutions than buying the software are relevant in the simulation business, by hiring a trained consultant, and leasing or renting software.

- Integration with CAD is pointed out as a key factor that enables the use of the CAD layout, imported in the simulation model true to scale and used as a geometrical reference for the model.

- Realistic visualisation was required by the industrial team to enable them to do presentations to potential customers, demonstrating the plant and the manufacturing techniques of new products. The idea was to record video files that could be shown in a PC and could easily be shared among others without the need for any additional software.

After a few simulation experts had been consulted, the situation became clearer. Finally, the software that corresponded to our requirements, and also a simulation expert willing to cooperate in the project, was found. Besides modelling and simulation the simulation expert
was required to support the simulation project team in training for the use of the DES software.

The DES software that met our requirements was found in AutoMod™ from Auto Simulations, along with the commitment of a simulation consultant working in the AutoMod environment. AutoMod has its focus on manufacturing and material handling systems, which corresponds well to our requirements as regards modelling conveyers, robotics and machinery. AutoMod also provides the facility to define the physical elements of a system using CAD-like graphics, represented in true scale dimensions and collision detection for moving objects. Visualisation and animation using the AutoMod simulation model also provides the value-added dimension of the dialogue with the market, according to the industrial team's wishes.

To execute the project a "simulation group" was organised, consisting of a technician from the industrial group, a qualified simulation expert, and 3 academics with some earlier experience of DES. Given that the specifications of the layout were complete and correct, the project was planned to be completed within 200 hours of efficient time and carried out in concentrated workshops of 2-3 days with the simulation expert present. The time between workshops, planned to be 2-3 weeks, was dedicated to carrying out tasks given in the previous workshop and preparing information for the next meeting. Organised this way the project was also planned to serve as a training programme for the group in techniques for modelling and simulation. Organised this way the project was planned to be carried out within 3 months.

6.3 Description of the manufacturing unit

Before embarking on the following chapters about the modelling and simulation stage, an introduction of the new manufacturing system is needed. The level of detail in this presentation is held on a level that provides sufficient information to understand the formulation of the accurate simulation problem. Specifications presented here were designed and provided by the industrial team at the time when the decision was taken to build the plant, and consist of detailed technical specifications for all equipment, together with a draft of the layout.

The plant embraces manufacturing equipment covering a physical area of 160 by 70 metres, or a total of 650 metres of manufacturing lines. In general, it can be described as consisting of five separate process lines for machining and intermediate buffering, besides the final line for surface treatment, which is not included in the study. The actual layout is illustrated in Figure 17, showing 5 separate lines (1 to 5), and the intermediate supply line moving material between each of the five process lines (6).

The system was based upon the following mechanical equipment, categorised into groups of conveyers, buffers, and robots (R) and machinery (M), as illustrated in Figure 17.

- Conveyers: a total of 550 metres of conveyer lines, of which 500 metres are longitudinal conveyors, moving objects by their length dimension, and 50 metres of cross-conveyors moving objects by their width dimension.
- Robots: a total of 16 X-Y-Z directional robots for up- and down-stacking, and feeding to the machinery. (R)
- Buffers: these are arranged by moving/sliding on cross-conveyors, stacking in Z-direction by robots, and intermediate buffering of stacked material, to a total of 30 buffers.
Machinery: processing of material refers to machine types such as planers, rip- and crosscut saws, sanders and other equipment, representing more than 40 process steps.

Figure 17 The manufacturing system, an overview

This tells us that conveyers, buffers, robots and machinery represent more than 40 horizontal direction changes in each one of the five processing lines. Over the total length of 650 metres, there are more than 200 directional changes in all three directions, x, y and z.

Products manufactured are based on the three-layer laminated panel, which is then refined into flooring and panels. This production is based upon sawn boards as a raw material, in a wide range of quality and in lengths up to 4 metres. Boards are then ripped into sheets of approximately 5 millimetres thick, which are glued together edge by edge to make larger sheets of 1.2 x 2.4 metres. The three-layer panels are built up of a top and a bottom sheet with a longitudinal grain (2.4 metres), and the middle sheet with its grain turned 90 degrees (1.2 metres). This three-layer board, or panel, of the size 1.2 x 2.4 meters is produced in various thicknesses and by using various materials in the top layer, alternative products are made. In floor products the top layer can be various kinds of wood in a parquet pattern or larger pieces representing a solid board. The panel is finally ripped into 4 boards, 30 centimetres wide and 2.4 metres long. The top layer can also be composed of a surface of solid wood, and the three-layer board can then be used as it is in various kinds of woodwork. The build up of this product and its variations is schematically shown in appendix 4.

6.4 Formulation of the simulation problem

Before starting a simulation project, it is crucial to formulate an accurate definition of the simulation problem; this is emphasised frequently in the literature. It can be summarised as follows: definition of the problem; how the model and actual simulation reproduce the problem; and finally the implementation of results in reality in relation to the original problem defined.

According to earlier presented and discussed conditions of the planned manufacturing system, the purpose of the simulation project was now formulated in a more stringent form as follows:
A. Analysis of the actual layout and material flow with its specification in order to discover bottlenecks and total output of the system.

B. Results from the simulation were planned to be put into effect by implementing proposals for minor redesign and adjustment of the actual layout.

C. A secondary purpose was to provide a 3-dimensional model of the manufacturing system and generation of animated movies that can be shared among interested parties.

D. Analyses of the origin specifications of the manufacturing system according to specific needs in developing a simulation model.

6.5 The modelling stage

The next step in the simulation project was to design the simulation model based on the original specifications provided by the industrial team.

The original specifications were first structured in geometrical and functional specifications. The geometrical specification was categorised into two types, one by the two-dimensional layout, one by three-dimensional specification of the design for each piece of mechanical equipment. Functional specifications consisted of two types, variables of material feed rate and process time etc, and description of logical sequences for material handling. For a majority of cases, logical sequences are related to programmable control systems (PLC’s) of machinery, conveyors and robotics, and describe how certain sequences will be performed. Most of these variables, such as speed, acceleration and wait stage, were linked to parameters that were easy to change in the model, to enable an accurate performance of the system.

With these definitions a general description of the modelling steps in AutoMod was as follows:

1. The first step in modelling was to import the CAD layout “true-to-scale” in AutoMod. In this way the layout served as a quick geometrical reference in the design of the model, by positioning objects, such as conveyors and machinery. Drawing and placing objects could also be done by X-Y-Z coordinates and millimetre precision, but the reference given by the layout provided sufficient accuracy, in this case by “snap” of 10cm. Dimensions of all equipment, such as width and heights, were provided by the original specification.

2. The second step is geometrical positioning of “stations”, which is an AutoMod unique definition for each geometrical position on conveyors where a moving object changes its states. A state refers to stop, start, moving direction, dimension, set of flags and much more.

3. The third step is programming of the logical sequences that tells objects their moving path and behaviour along the defined path of buffers, conveyors and machines. Programming is based on an AutoMod unique syntax that handles references such as “stations”, which are needed to define the complete simulation process.

4. AutoMod also contains modules for modelling special equipment such as robots, bridge cranes and automated trucks. The module for robotics became useful for modelling all the 16 pick and place robotics. For the design of robotics and other detailed information about modelling in AutoMod, the AutoMod Manual provides more detailed information.

The structure of the model was divided into blocks, or modules, related to each individual piece of equipment as it was organised and indexed in the original specifications. Figure 18 illustrates how specifications of geometry, logical sequences and variables are related to
specific equipment and index. In this way each process, or cluster of associated processes, had its own programmable file and geometrical reference.

The layout, consisting of 5 separate manufacturing lines, which in the model could be simulated separately, is illustrated by line 1 to 5 in Figure 18. Line number 6, constitutes only material handling which serves other process lines.

This model structure illustrated in Figure 18 provides an insight into the structure of a model of this rather large size. The figure also illustrates a structure of the model based on modules, that makes it open and editable for implementation of further functionality of wood characteristics etc.

![Figure 18 Structure of the simulation model](image)

Another concern in modelling is the management of in and out data from the model. In our case working with AutoMod, this was managed by a Microsoft Excel interface. This implies that all information, both in and out data, was collected in an Excel file that could be designed for whatever was needed.

### 6.6 Problems in modelling

As described in chapter 4.2 by Figure 15, the simulation project was initially intended to be a stand-alone project, which was not involved in the actual development process of the plant done by the industrial team. Its main purpose was to validate the original specifications and the manual calculations of productivity, as described in the first point in chapter 6.4, where formulation of the simulation problem is in focus.

When the simulation project took place, it proceeded by analysing and structuring original specifications, as described in the previous chapter. However, it was soon found that this work of information modelling was considerably more time-consuming than estimated in the prior planning of the simulation project. Typically geometrical references and descriptions of functionality for individual equipment were not coherent according to the requirements for building the model. A number of design problems therefore had to be solved interactively with the development of the simulation model.

Further conditions were raised that complicated the later part of the modelling stage; this was a result of major changes in the layout due to other equipment being acquired than what was specified originally. The choice of other equipment was a decision taken by the industrial team because of a more attractive investment alternative. This was done without any prior consulting with the simulation project. Nevertheless, as the technician was involved in both
the industrial activities and the simulation project, these changes were eventually implemented in the simulation model. All the new equipment implied that specifications became even more insufficient; a number of problems that were actually not solved in reality now became solved interactively with the design of the model.

Typically the new equipment acquired implied a redesigned layout. However, in the end these problems also concerned detailed design. Detailing was either given by specifications of the new equipment, or worked out interactively with the design of the simulation model.

6.7 Design work supported by modelling

The previous chapter describes some of the background concerning how the simulation project changed direction and became used to solve a number of design problems. Typically design problems that occurred could be categorised into two types, detailed design problems, and layout design. Layout design concerned general logistic issues and strategies, involving location and geometrical dimensioning of various pieces of equipment, such as conveyers and buffers, feed rate and distances between operations etc. Detailed design concerned, for example: functions and design of material stops, direction changes, and turning of moving material, along with positioning of sensors and sequencing of the material flow. These detail design problems became intimately related to the design of mechanical equipment of various kinds and control equipment, such as sensors and process sequences. In particular the design of material handling equipment, such as conveyers and “pick-and-place” robots, was a major modelling activity.

When solving these two kinds of problems, interaction with the simulation model was outstanding for both layout and detail designing problems. A typical case of a detailed design problem being solved simultaneously with development of the simulation model is illustrated in Figure 19.

The figure shows a buffer on a cross-feeding belt conveyor with 2 positions on the belt where material is positioned, F and D. Where boards are positioned, in F or D, determines whether the boards will pass the glue spread machine or not, before they are stacked by the pick-and-place robot. The process is described in detail as follows: Incoming boards (upper left part in the figure) are moved sideways into the conveyer belt, and are then moved until they hit the mechanical buffer stop (A). A batch of four boards is then moved into position D as soon as clearance is given. At the clearance signal (B) obtained by the rear end of the previous batch of boards passing the sensor in front of the glue-spreading machine (C), the mechanical stop (A) is lowered. Feeding then continues with the batch of four boards, which are positioned in front of the glue-spreading machine. After four boards are counted into the positioning area, the buffer is closed by lifting up its mechanical stops. Before feeding into the gluing zone starts, clearance must be obtained behind the glue-spreading machine (E), accomplished by the fork arm of the “pick-and-place” robot picking up the boards and stacking them on the conveyer that feeds into the glue press. This sequence continues nine times, and boards are stacked by the robot in front of the glue press. The tenth and last layer of boards in the stack is positioned in (F), since they do not need to be glued. When a batch of four boards is positioned in (F) they are moved into the range of the robot, stacking the batch on top of the other nine boards. This process is further illustrated in appendix 3.
In the previous section a typical case of a design problem and its detailed solution is outlined. The workflow contained a number of iterations, but can be structured in the following generic description.

The design for such a case was initiated by making the three-dimensional moving path for the material contain “stations” that involve some kind of status change or check point for the moving material, see Figure 20. This structure constitutes a kind of skeleton for the model, and in this way each component of the layout specification was verified by making the moving path continuous. Based on the initial specifications, a number of missing information of both a geometrical and a logical nature was discovered in this way in the model. In order to make the material flow and process sequences continuous, the model served as a reference in verifying each part of the line. Results from this work usually implied rather extensive changes in the original specification layout, changes that were later implemented in the real system.

The next step in the workflow implied the programming of the logic for the model, a task that implied each sequence of the manufacturing process being implemented in simulation program code. This is also the point when variables are implemented in the program code of the model. In this case the variables were limited to only dealing with feed rates for the conveyers. Furthermore, wood was not given any attribute more than geometrical dimensions. Rather simple and easily made graphics, representing equipment, were also added to the model at this stage. In some cases of robot and conveyer design, graphics were added early in the design of the model to enable understanding of material movements. In some cases more detailed graphics were needed to provide a complete understanding of the problem, and were then added instantly. Otherwise, detailed graphics were added when the design of the simulation functions was finished. It should however be emphasised that the design of the layout, described as a “skeleton” above, and shown in Figure 20, contains a three-dimensional representation with visual references that continuously supported the model design during the entire work process.
At this stage verification of the model was based on recurrent visual examining of the material flow, both statically and dynamically. Along with automatic collision detection between moving objects, a rather realistic material flow could be created that enriched the problem-solving dialogue between the simulation expert and the technician from the industrial project. Examples of various results from alternative settings of variables for the feed rate are shown in appendix 3 by snapshots taken of alternative settings. Verification of the model could therefore involve anyone who might be concerned, regardless of their prior experience of DES fundamentals. While the original documentation did not always provide detailed information on feed rate and order of sequences, such information was fairly easy to obtain by running a simulation under different sets of variables. If changes were needed, these were implemented in the model, simulated and verified in a rather smooth way.

It was obvious that an enriched dialogue occurred, particularly between the simulation expert and the technician from the industrial project. In this way, real design problems were solved and the simulation model became increasingly developed, along with the updating of the plant layout and its functional specifications.

6.8 Completion of the modelling stage

Geometrical information was frequently missing, although, original specifications were briefly examined by the simulation expert at the start of the project, and judged to be sufficient for the design of the model. Moreover, people in the industrial group were convinced that the specifications of the plant were very complete and of high quality. However, missing or incomplete specifications provided by industry, constituted a time-consuming problem throughout the whole modelling stage. The previous judgement regarding the specifications of the plant, provided by the industrial group, was obviously insufficient, regardless of whether it was a case of building a simulation model, or building the plant in reality. The quality of specifications of the plant was simply overestimated. This fact forced us, and in particular the technician, to penetrate the original material in detail, as well as the design of the simulation model.

During the entire modelling stage, detailed answers to a number of questions had to be straightened out. Solving these problems led to a number of creative discussions on the design and alternative manufacturing techniques, not only on a detailed level, but also concerning
more overarching questions regarding the layout. The most striking result to emerge from the
design process was the elimination of two robots, priced at approximately 1 million Swedish
crowns, (or four times the budget of the total simulation project).

Then further problems or hindrance to modelling occurred when the industrial group made a
major change in the manufacturing lines. This was caused by the acquisition of other
equipment from the used market, which could provide a better capacity at a lower price.
These changes, and some further ones, were implemented in the simulation model by
redesigning the parts in question. However, redesign of the layout was then constantly going
on, and changes in the layout were more or less randomly provided to the simulation group
for implementation in the simulation model. Accordingly, due to insufficient specifications,
changes and redesign of the layout after the final design, the simulation project had now been
slowed down radically. Finally, the limit of the project budget was reached, which was
financing the senior simulation champion.

At this point, a decision was taken to pause the simulation project, even if the model was not
equivalent to the actual layout of the plant and its continuous development. It was then
decided to wait with changes in the modelling, while changes in the layout carried out by the
industrial group seemed to continue. The model was anyhow complete enough for simulation
of a variant of the entire manufacturing process, so it could fulfil the request of animation.

6.9 The simulation stage

As clarified in the previous chapter, the simulation project was interrupted because of
recurrent changes in the layout carried out by the industrial group. Thus the actual version of
the simulation model corresponded neither to original specifications, nor to the final design of
the plant that was still not defined. This was in conflict with the simulation problem (D)
declared in chapter 6.4, “Analyses of the original specifications of the manufacturing system
according to specific needs in developing a simulation model”. A number of changes in the
layout had already been made in order to complete insufficient specifications and enable the
design of the simulation model. In other words, it was already established that the original
specifications were not complete, not for making the simulation model, and even less for
building the plant.

The decision to interrupt the project indicated that the model did not correspond to a number
of changes executed by the industrial group at a rather rapid pace. The simulation model
represented at least a variant of the entire manufacturing system. Thus the model also fulfilled
the request for making animated movies that could be produced to illustrate the
manufacturing technology and the product processed for each individual line. This implies
that the task defined as simulation problem (C) was fulfilled.

Simulation problem (B) defines that implementation of results from the simulation analysis
was planned to be used for minor redesign and adjustment of the actual layout. Since the
simulation project was interrupted before the plant design was accomplished, simulation
could not be validated against the real layout design when it was finished. A simulation
analysis failed in the way defined in (B). However, redesign and adjustment of the
manufacturing system became reality beyond all expectations, not as a result of the simulation
results, but by the design of the simulation model. Incompleteness in specifications and
improvements of the layout were indirectly solved during the modelling stage by the design of
the simulation model. The most striking and financially measurable result of this task was the
elimination of two “pick-and-place” robots However, the initial simulation of problem (A),
that considered a simulation analysis of the entire layout in order to discover bottlenecks and
total output of the system, was hard to carry out for reasons presented above. Moreover, some
input data was still not implemented in the model. At this stage the input data was just related to equipment by variables, such as process time, speed, and what was needed to describe the material flow through the entire process. Machine breakdown, repair or any other statistical distributions caused by the effects of wood quality or other factors, were not implemented into the model at this time. Completion of the model, when production had started and more data could be collected, was discussed.

One part of the model, defined as line 1, shown in Figure 17, nonetheless corresponded quite well to the real layout design by manufacturing. Therefore this part of the system was focused on for an analysis by simulation.

At this stage the purpose of the simulation analysis was to balance the material flow. The dynamics of the material flow was mainly based on variables for feed rate, process time, and wait stages. By using initial values given by the original specifications, some adjustments could easily be made, and then validated by visual examination of the material flow. It was obvious in this initial attempt at simulation, that the model provides extensive insight into the dynamics of the material flow, just by visualisation of the manufacturing process. Even small trends of “bottleneck” effects in front of one machine were immediately observed, and adjustment of variables in the model could then easily be made in order to achieve a harmony in the material flow.

In one case, a bottleneck developed very fast, and no adjustments of variables could compensate for a bottleneck building up. This case of a bottleneck is illustrated in Figure 21, and later occurred in the plant, resulting in further redesign of the line.

![Figure 21](image)

Figure 21 A “bottleneck” is built up.

By carrying out some simulation trials of the entire system, further bottlenecks were encountered, and a number of questions were raised with regard to the material flow and alternative manufacturing strategies. In particular batch sizes were a matter that had not been considered in the original specification, at least not with the insight that was possible by using the simulation model.

6.10 Visualisation

The requirement of animated movies from the industrial group was a factor that to some extent forced the project to create a more detailed model with visualisation than required for a traditional simulation problem. However, the use of these movies was successful since a number of customers, suppliers of raw material etc, could in this way quite easily be introduced to the manufacturing concept.
Further use of the visualisation features in the simulation model was found in education and training. This was applied to groups that were put onto training programmes in preparation for a possible employment at the plant. By running the model in “simulation mode” the entire group could examine the entire manufacturing process. Moreover, various ways of organising work functions were discussed in the group with the model as a reference. A case where such a dialogue was especially fruitful concerned the organisation of the repair and maintenance people and the planning of their tasks. This simple trial of applying the simulation model to the training programme was very much appreciated in the group, particularly since no one had previously seen anything of the plant that was still not built.

Visualisation was also found usable in communication within the simulation group, entering design problems during the simulation stage. This was done with pictures taken as “snapshots” of the simulation in various situations, showing the material flow together with equipment. Pictures were then enriched with arrows and explanatory text, and sent by e-mail to be judged by the other party. In this way a manufacturing problem could be examined both visually and clarified by text with references that were generated direct from the design of the DES model. Actions could then include redesign of mechanical equipment, as well as adjustments of sequences in the material flow. Additional possibilities for such a dialogue could also be based on VRML models (Virtual Reality Modular Language) of the entire plant that could be shared among team members, as shown in Figure 22. However, this was not explored fully, since pictures alone provided rather good information, as shown in Figure 19, and were also easy to edit and send by e-mail.

![Figure 22 The plant shown in web browser as a VRML model.](image)

Since a great deal of the mechanical equipment in the manufacturing system was custom designed, issues that were related to mechanical design were frequently in focus. At the end of the simulation project, a new program release of AutoMod was provided for us. This version of the program also enabled the import of VRML objects, representing mechanical equipment or people, for example. Usability of this feature was not explored in the project, but became obvious in our experiences in the project. This is mainly concerned with the possibility of working on the design of mechanical equipment in a 3D CAD system, and then importing the CAD model into the simulation model using VRML format. In this way, a new machine design could for example be further improved, by analysing its function in the simulation model. Moreover, such procedure would be of advantage in order to improve the quality of the simulation model.

In an extension, the import of VRML objects could imply that machine suppliers provided VRML models of their equipment. This possibility was discussed with the German saw manufacturer, Winterstieger, from whom equipment was ordered for the plant. In the actual
simulation model this machinery from Winterstieger is shown in the left part of Figure 23 as a simple 3D object in the model. By an export of CAD model in a VRML format, the actual equipment could also have been provided by Winterstieger, as is shown in the right part of Figure 23.

*Figure 23* VRML objects provided by the machine supplier.

In this way geometrical dimensions and positions of sensors, such as photocells etc, could have been provided by the VRML model as a support to the simulation model design. Moreover, such a VRML model could be enriched with machine-individual data as an attribute, for example, ratio of production capacity according to various feed rates, tooling and requirement of maintenance, information of great value in the model work.

### 6.11 The industrial team reflect on the simulation project

A final series of interviews and discussions with people from the industrial team was carried out during the spring of 2001. At this point most of the equipment was installed, and production was running for most of the floor products, except the line for parquet flooring. Tuning of various process parameters and synchronisation of batch sizes to market orders were some of the main issues present, running production by half of the planned output.

The industrial development team and their representatives were primarily exposed to results from the simulation project by the movies created and used in various presentations. Individuals in the industrial development team that were involved from the beginning of the simulation project were mainly informed about the simulation project by the technician within the group. A deeper insight into what modelling and simulation actually stands for, was only obtained by the technician that was working intimately side by side with the simulation expert during the entire simulation project.

The following four issues were discussed with the technician, the consultant, and the entrepreneur, all of whom were involved from the beginning of the project. The managing director, who entered the project at a later stage, was also involved in the study.

1. Acquisition of alternative equipment changed the original concept and caused an extensive redesign and delay of the start-up of the plant. How was this evaluated in relation to the profitable price of the equipment?

2. What is your conception of DES, and how could it have been involved in the development process from the start?

3. Since it was accomplished here as a stand-alone project, has the simulation project supported the real development project?
4. Do you see any use for a DES analysis today, for solving manufacturing problems now that production is actually running?

The first question has its given answer. First, some of the alternative equipment was more efficient than specified originally, all at a price that implied financial advantages for the project. Therefore, even if redesign of the final concept had to be done, and in some cases simultaneously with the installation of equipment, the benefit of changes was obvious.

In answer to the second question, all parties agree that DES could have been used from the initial stage of the development process. However, this answer was difficult to justify fully for anyone other than the technician, who was more closely involved in the simulation project than others. His justification for this also provides an answer to the third question, regarding how the simulation supported the industrial project. At the start of the simulation project, the technician was in the process of studying the original specifications of the plant layout. This was in order to assist during the following installation and tuning of the system. Being involved in the simulation project indicated that each object and function of the manufacturing concept had to be penetrated in detail by both the technician and the simulation expert. Besides solving design problems, the technician was in a situation when he had to gain knowledge of each part of the entire layout. Due to the interaction with modelling, his learning about the plant was both improved and more time-efficient. Moreover the simulation team, and particularly the cooperation with the simulation expert, provided a context of innovative climate. The experience of the expert from many prior projects, along with modelling that embodied the manufacturing system, were described as the major factors for discovering and solving problems that were related to the original specification.

Regarding the fourth question, new problems had been discovered and the question had arisen concerning the further use of DES for solving these problems. The main problem was to match production orders in order to market demands in optimal batch sizes. In particular since the product-register now consisted of 36 product types, defined by various lengths, widths, and thicknesses in the same kind of wood. Moreover, at least 10 kinds of wood were possible for the top layer, and each product needed to be sorted into A and B quality before they could be delivered to the market. Coordination of market orders into efficient batching was now very difficult to manage, mainly because of the size of the plant and the difficulty of taking in the whole situation of the dynamics of the material flow. This insight was obvious to the technician, who had now entered the position of production manager.

6.12 Summary of the simulation project and its results

The following description is a comprehensive summary of the simulation project. This includes the initial plans for carrying out the project, which were then influenced by the actual conditions in connection with the industrial project.

First, the simulation project was intended to be a stand-alone project, not involved in industrial development activities. The main purpose was to evaluate the original specifications of the plant that were manually calculated, by manufacturing simulation. Based on the original specification, a simulation model was assumed to make a dynamic analysis of output and bottlenecks in the material flow. Other purposes of the project were to evaluate to what extent DES was a proper tool for the actual problem, i.e. simulation in early development stages when no physical references are present.

Another future plan, or idea, was to conduct a second evaluation of the plant when full-scale production was in progress. The purpose of such a study would then be to validate the
reliability of the previous simulation model against conditions of the real manufacturing process of floor products. These assumptions and plans are illustrated in Figure 15. As the simulation project started, problems arose because the original specification was not sufficiently complete to support building the simulation model with accurate data. Missing specifications were of the kind that would have been needed sooner or later in the installation procedure of equipment in the plant. This means that the specifications were needed, regardless of the design of the simulation model. The design of the simulation model had the effect of bringing these problems of incomplete specification to the surface earlier in the development process and solving them interactively with the design of the simulation model. A number of design problems were penetrated and were in this way solved by the design of the simulation model. However, the simulation project turned out to be informally involved in the industrial development activities of the plant. Consequences of the original plans for the simulation project meant that it was delayed for more than a year. The initial purpose of the project to evaluate the original specification was not relevant any more, since specifications had already been found to be inaccurate in a number of respects.

Further conditions occurred that influenced the simulation project, this time due to the action of the industrial group and their acquisition of other types of equipment than specified. Even if this was an attractive business deal, further design problems had to be solved by redesigning the layout. The current version of the simulation model also had to be reviewed and redesigned in accordance with the new equipment and changes in the layout. These industrial activities were typically performed without any prior dialogue with those working in the simulation project, ignoring the fact that simulation could have been a valuable tool to evaluate alternative investments in equipment. Reasons for not utilizing simulation were explained by the fact that the simulation project was initially a stand-alone project, not organisationally integrated in the industrial activities.

Nevertheless, development and redesign of the simulation model continued, and design problems were frequently discovered and solved in connection with the new equipment that had to be implemented in the model. Design work was performed in cooperation with the technician of the industrial group, as he was a participant in both the simulation project and the industrial activities. A number of creative design tasks were carried out on both equipment details and layout.

Finally, the simulation project had reached the limit of the financial budget and had to be stopped. The simulation model now represented the entire manufacturing system, with the exception of some parts that were still the object for redesign by new equipment. The model could comply with the industrial group’s desire for visualisation of the plant. Another positive aspect credit of the project was the saving on two “pick-and-place” robots, which were eliminated as a result of creative design work performed in the simulation tool by the simulation expert and the technician. Last but not least, according to the technician the opportunity to work through the entire system, part by part, as a result of the design of the simulation model, was of great value in his learning process of the plant.

Development of the plant had still not come to an end when the simulation project was ended. There was still at least 6-8 months of further work in conjunction with installation and adjustment of equipment before manufacturing could start on a small scale. It could be questioned why no further contribution of financial resources was arranged, since valuable effects of the simulation project were found. The first reason was that the simulation project not was integrated in the industrial activities. Moreover, the involvement of the technician was subordinate to the management of the industrial project, and all other tasks that he therefore had to execute. Finally, being in the middle of these activities does not prove the
perspective and wholeness of the project; it is easy to be wise after the event, and ‘know’ how things should have been done.

Altogether these conditions discussed above are illustrated in Figure 24, a revised edition of Figure 15. The figure illustrates particularly how the simulation project was more extended than planned, and provided a design support. Moreover it can be seen how industrial activities to develop the plant continued after the simulation project had ended. It was also found that a critical point of design freeze never existed.

![Studies within the industrial development project](image)

**Figure 24** The outcome of the simulation project.

The following list is a summary of results that are of crucial importance with regard to the problem areas outlined in this thesis.

[I] The original specifications of the manufacturing system could not supply enough information for the design of the simulation model, even though the specifications were considered to be absolute by the industrial team.

[II] Initially, the academics’ conception of the industrial project was idealised in some respects, in that it assumed the design to be final at a certain point of time. Or, seen from the perspective of the industrial team, the requirements and the potential of the simulation project were underestimated. At the time when the simulation project was initiated, there was no coherent dialogue between these two parties.

[III] The original specifications were completed simultaneously with the design of the simulation model, greatly supported by the accuracy of the specifications required for the design of the simulation model.

[IV] If no simulation model had been built, insufficiency in the specifications would have been solved by an alternative method.

[V] Both detailed design, intimately related to mechanical design, and layout design were solved interactively with the development of the simulation model.

[VI] Detailed design in the simulation model is very closely related to mechanical design, and there was reciprocal interaction between mechanical design and model design. A key feature that enabled detailed design was 3D representation of the simulation model, which implied integration between mechanical design and material flow analysis.

[VII] Visualisation of the plant enabled an enriched dialogue that involved collaborators in the modelling stage, even if their knowledge of DES fundamentals was poor.
involvement of collaborators in the modelling stage enabled a qualitative verification of model design, step by step.

[VIII] The simulation project was based on what was generally considered as the final design of the plant, and intended to be a separate project, which did not interact with industrial activities.

[IX] Because of insufficiency in the original specifications, and further changes in the actual layout design, the design of the simulation model became informally involved in the industrial design process.

[X] Tangible results, such as the elimination of two robots and a number of improved design matters, were generated during the design of the simulation model.

[XI] The simulation project was interrupted because of recurrent changes in the layout, made by the industrial team. These changes could not be implemented in the model systematically, or within the budget of the simulation project.

[XII] The technician experienced an efficient and creative situation, being a participant of the simulation project. This implied acquiring knowledge about each component in the manufacturing system, solving problems that were discovered, and developing potential during the entire modelling stage.

[XIII] At present there is a need for further analysis by DES, for efficient coordination of market orders according to batching of manufacturing in the alternative manufacturing lines.
7 ANALYSES AND REFLECTIONS

Results from chapter five and six are synthesised in this chapter with regard to the theoretical framework and the three problem areas presented in the introduction. The industrial case is an example of a conventional development process in industry, entailing conditions in which DES has to be integrated.

7.1 The development process

There are many reasons for exactitude in a development process and these increase as the project becomes more complex. The need for a proper pre-study and definitions of design criteria can unmistakably be explained by the significance in achieving a convergent development process. The industrial development studied can in different be categorised as divergent, where problems and specifications have been underestimated or disregarded in the early development stage. By carrying out the simulation project, insufficiency in the specifications was discovered and considered while design freedom was still possible. Specifications for the entire manufacturing system were worked through in detail, in conjunction with the design of the simulation model. This resulted in a number of valuable results, of which the following are considered as the most important conclusions:

- A number of design improvements in the real system were developed and verified within the design of the simulation model. The DES tool that was used enabled a flexible and creative design process.
- There is a need for improved methodologies and computer support to improve quality of specifications for the kind of industrial project that was studied.
- A great advance in the learning process of the system was achieved by the technician that was involved in the simulation project. Visualisation constitutes a vital factor in DES that supports communications in various contexts, from verification of technical systems to information and education/training.

On the other hand, the validity of these conclusions can be questioned. We can ask ourselves whether the specifications studied constituted an occasional case of insufficient information, or if conventional development methods in general imply specifications of this quality.

A further aspect to consider is the definition of the final design, or the design freeze, or if such a status occurs in a project of this kind. According to the simulation group it was believed that the decision to build the plant also implied that the design was final and permanent.

According to the management of the industrial project, specifications of the plant implied enough information to make the decision to carry out the project. This was a decision that was also based on the crucial factor of financing the plant, which was a condition that had recently been fulfilled. Obviously the signification of the final design was not fully clarified at the point when the simulation project was initiated.

Resuming the initiation of the simulation project, triggered by the decision to build the plant, the industrial representative was convincing when describing the accuracy of the specifications. The application of DES also meant that a number of problems were discovered and solved just by modelling. Furthermore, the acquisition of other equipment than planned, constituted further changes in the specifications. This was a striking observation to witness; the industrial team undauntedly made changes in the original specifications without considering a more detailed consequence analysis. At least problem solving within the
simulation project in connection with the new equipment indicated that a number of questions had not been overlooked.

Evaluation of the alternative equipment could have been done in respect to keeping the original layout design, which was associated with certain guaranties of production capacity. Profit from a favourable business deal regarding the equipment could then have been analysed in terms of consequences in redesign and loss of manufacturing volume caused by a possible delay of production start.

It was later found that redesign and adjustment of the layout was carried out for a long time by the industrial group, in close connection with the installation of equipment. Today, in spring 2002, there are still parts of the plant concerned with manufacturing the blocks for parquet flooring that are still not complete and have not been put into operation. To enable the production of parquet flooring, the top layer is bought from subcontractors.

In a generalised interpretation of these findings, it can be assumed that changes in specifications are probably not uncommon. Particularly in the case of a small industry with limited resources, business opportunities and possible resources must be exploited with flexibility. Conditions of this kinds show whether a DES tool enables flexibility to allow changes in the model as opportunities arise or changes has to be done.

In order to improve the development process of this kind, there is a need for a descriptive model that provides a guideline in the development process. Such a model is not intended to be followed exactly; it should have flexibility, it should be possible to develop, and it should consider the integration of computer support. According to Ulrich and Eppinger [1995], the main purpose of such a model is to provide:

- a structure that makes the decision process explicit
- a "checklist" of the key steps in the development process
- support for documentation of the project.

7.2 Decision support

Since the industrial project studied here was initiated on quite a small scale, informally and with limited resources, the activity of acquiring resources and confidence was important. The conception of what is considered to be a final design in this context can therefore be widened to also include the information on which financiers base their decisions. Unfortunately this group has not been included in this study, but it is known that in the dialogue between the entrepreneur and financiers, the layout and specifications constituted a crucial component. Besides financiers there were also a number of third parties involved, such as collaborator of various kinds, local government and other authorities. These parties also based parts of their standpoint on the technical specifications provided concerning the planned manufacturing system.

It has already been established that the simulation project became of vital importance in the process to improve layout design and its specifications. Moreover, these improvements could be verified by the simulation model, which provided vitality and creativity to the design process. Visualisation in the model also enabled the involvement of supporting competences, that could examine the model to verify and validate the design of the model as it was being developed, step by step. An example of such involvement is the technician with special knowledge in wood and wood processing techniques, supporting the simulation expert. Another example is the involvement of financiers and other third parties; by a simulation analysis they can be provided with detailed specifications, a dynamic capacity analysis, and a
simulation model that verifies specifications and the dynamics in the material flow in 3D graphics. In comparison with the content of the material that was provided initially, it is shown that a simulation model provides a decision support in various contexts that widely enriched the quality of development process.

These findings gave insight into an application area of DES other than the traditional one, where it is used for validation of decisions that have already been taken. In contrast it is here integrated in the design process by:

- improvements of design solutions as a result of an instant verification by dynamic analysis
- improved model quality using graphics, enabling the involvement of supporting competences.
- improved knowledge of a planned system connected to better decision support.

7.3 Dimension of modelling

For various reasons, the simulation project became informally involved in the industrial development activities. This was, however, a fortunate development of the project, in that it put problem solving and design issues during the modelling stage in focus. Both layout design and detailed design were solved during the modelling stage. Design solutions could also be verified step by step, by running a model in simulation mode.

Kelton et al [1991] emphasise that a simple tabletop-scale model can be of great support by embodying a system that is in focus for a simulation analysis. However, at that time computer graphics were not developed to the same extent as today. Visualisation in DES tools is further discussed by Rhorer [2000] “Seeing is believing”. Rhorer mainly focuses on verification and validation supported by visualisation. A general perspective on models and modelling is provided by chapter 3.4, Models or prototypes. While there are no distinct definitions of when the model turns into a prototype, theoretical references discussing prototyping and prototypes provide a more comprehensive picture.

Reflecting upon the work done in the simulation project, it has much in common with prototyping and a creative design process, as described by Schrage [1993]. Schrage discusses the potential of determining specifications by reciprocal action with prototyping. He also discusses how prototypes can be used in prototyping, which can be seen in the analogy with our DES model used in problem solving in the simulation project. Schrage discusses the significance of a prototype or model: why it is made and how it is used in the development process (See Figure 9, "The Prototype Culture Design Matrix").

Depending on how the simulation model was used, or could have been used, similarities can be found. In particular visualisation of the simulation model constitutes a new dimension in DES that better enables involvement of other competence fields supporting the simulation expert. Certainly, simulation results are provided numerically and by diagrams, but a 3D simulation model constitutes more than that in its lifecycle. Used in the early development stage a model could have been used to improve the dialogue with authorities and local government. Internally, within the simulation project, it is evident that the simulation model supported the design process of both the layout and detailed design of equipment. In both these cases the matter of verification and validation is the key.

It can be established that the use of a simulation model in a development process is an analogy to the use of a prototype in prototyping. As previously stated in chapter 7.1, there is a need for structure and support in order to achieve an efficient integration of computer support.
Such a model should also consider the dimension of visualisation enabled by DES and other VM tools used in models and modelling. Exploiting this dimension of prototypes and prototyping, or models and modelling, requires a consciousness from the management to organise the activities and resources needed.

7.4 Wood manufacturing system design

In the introduction the wood manufacturing industry is outlined as an industrial sector where DES is not frequently used. This is usually explained by the difficulty of reproducing the complexity of wood properties in a DES model. When a piece of wood is split and cut into smaller components, quality is difficult to calculate in advance. Even if historical data from breaking down identical raw material sources is used, quality results are difficult to estimate in advance.

In the simulation project studied here, no variables were defined in the model to represent the quality parameters of wood. To what extent the properties of wood, and their influences on the manufacturing process, could be implemented in a DES model could therefore not be evaluated. However, other conclusions that are unique to wood manufacturing can be established. These results are linked to a similar kind of production studied here, which can be categorised by:

- relatively large physical components
- short processing time in relation to time used for material handling between process
- large physical volumes to be moved and stacked efficiently

Moreover, the dimensions of each object (piece of wood) and the distance or contact between them, when moved on a conveyor or something similar, are crucial factors to consider in such a material flow. These conditions were reproduced by the model to an extent that greatly exceeded the expectations and requirements listed in chapter 6.2.

The realistic reproduction of the material flow could be done with such quality that it constituted a factor of essential dignity together with the incorporation of stochastic variables. Moreover, in real life the collection of production data often requires questioning and dialogue with people experienced in wood manufacturing, in addition to statistical information on the material being processed.

The visual reference provided by a 3D model with a realistic material flow is of crucial importance in the dialogue with the experts in various fields of competence about how quality parameters should influence a model. Visualisation by a simulation model enables shared values and references among all those involved, which can be seen as a dimension of prototyping (or modelling) previously discussed. Another feature in AutoMod that enables a realistic design of a material flow is the function of photocells, a commonly used component in wood manufacturing.

It was also established that problems related to layout design, solved in the DES-tool environment, later also included guidelines for the design of mechanical functions. This design work carried out can be described as a creative and innovative design process, supported by visualisation of the simulation model. In this context, a new function in AutoMod (v10) makes an excellent development feature, by enabling import of VRML objects in a simulation model. A VRML object can be made in a simple VRML editor, or exported from most 3D CAD systems. Whatever kind of object needed to reproduce the manufacturing process can then be imported to the model. This function illustrated an integration of CAD-designed equipment, exported from CAD in VRML format, into a DES
model, as discussed and shown in chapter 6.10, Figure 23. The vital importance of this feature comes with verification of mechanical equipment with functions in a material flow, which is a common problem in the development of a wood manufacturing system and its equipment.

Integration of CAD objects as a support for model design by geometrical references is discussed by Paprotny et.al [1999], where a type of standardised information exchange between CAD and DES was illustrated. Moreover extensive research activities are in progress with the development of the STEP standard, that also includes the manufacturing process. These moves towards standardisation aim, for example, to create an efficient and secure exchange of information, which is independent of the software used, and they are generally addressed to conditions in large industries. Whether standardisation of this kind is applicable to project conditions in small and medium-sized manufacturing firms in the near future can be discussed. If not, there is room for support of creative and flexible design methods that utilise all kinds of features provided by software vendors.

It can be established that experience from the simulation project has shown that there is an application area of DES among wood manufacturing industries by:

- making it possible to reproduce a realistic material flow
- verification of mechanical design

These two conditions incorporated in a DES model enable a development and dynamic analysis of the entire system that greatly exceeds the information provided by the simulation project. Regardless of whether the properties of wood are built into a model or not, the dynamic analysis by DES, provides possibilities which cannot be compared with conventional methods.

### 7.5 Virtual wood manufacturing

The simulation project showed that a material flow of the kind that is usual in a number of wood manufacturing industries can be reproduced in a DES model. The model was extremely detailed in terms of physical references, such as material-handling equipment, machinery and moving pieces of wood, all represented in true-to-scale 3D geometry. Moreover reciprocal benefits were shown as a result of integration between mechanical design in CAD and the dynamic analysis of material flow by DES. As an example of this kind the import of VRML objects has been described and illustrated in Figure 23, chapter 6.10.

Beside these positive findings it was also shown that the model could not be changed without considerable work in connection with the new specifications of equipment that were provided. This highlights the question of whether the simulation tool provides flexibility to allow easy changes and redesign of a simulation model.

Regarding the conditions in which the simulation project was initiated, the model was based on what was considered as the final design, (which can also be criticised as a naive perspective of the problem). The purpose of the simulation project was to evaluate the accuracy of specifications; after this it became involved in design activities. Alternatively, in a simulation project with the aim of developing a manufacturing system, the simulation tools would have been used differently and together with other VM tools. Work could have been initiated with a number of rough conceptual layouts in CAD with related simulation analyses. Then by further development of the final concept a detailed simulation would have been of current interest.

Evaluation of DES tools was not included in the aim of this study, but since the question has been raised, two categories or trends can be defined among DES tools. One category is based
on a user-friendly Windows interface that enables model design by “drag-and-drop” of icons, and entering data in pre-defined windows. These kinds of tools are smooth to use, changes can be made relatively easily, and they are easy to learn; the use of these tools is therefore often categorised by the expression “quick and dirty”. On the other hand they do not provide the possibility for the design of a detailed and large model.

The other category is certainly Windows compatible, but has a unique modelling environment, or interface, that enables a detailed programming of various functions in the model. These tools enable design of both detailed and large models, and are the kind of tools that were used in this work.

However, these more complex tools also provide possibilities for a “quick and dirty” analysis, even if it is not done by “drag-and-drop”. Another possibility for fast track modelling generation is by importing SDX code (Simulation Data Exchange) into the simulation tool. In this way the simulation code is generated automatically, and when it is imported in the simulation model it provides a functional model that can later be developed and customised. Generation of SDX code can for example be carried out by a process-mapping tool or a CAD tool. A CAD solution of this kind is provided by Engineering Automation Inc. (EAI), where the layout drawn by CAD, contains “smart objects” that generate the SDX code.

Given this background, it can be questioned whether it was a proper approach of this research to only focus on DES, since its true value is when it is integrated among other tools within the domain of Virtual Manufacturing (VM). Moreover, the simulation project was a detached project, not incorporated in the industrial organisation that actually managed the development of the plant. Information about changes in the real layout was provided informally to the simulation group, mainly just to enable redesign of the model. Likewise the redesign of the model provided new creative solutions in return for being implemented in the real layout. It should however be emphasised that the innovative design generated in the model, was not a result of a DES tool itself. It was a result of extremely creative cooperation between the technician and the simulation expert, equipped with a versatility tool that united their thoughts. In an expanded perspective the entire industrial organisation, working with the development, could have been incorporated in a context based on an extensive use of VM. Such an approach enables cross-functional work, where ideas and design solutions are generated and shared among all participants by a virtual model. This illustrates that every person involved will have a detailed insight into the entire manufacturing concept, a crucial factor for generating practicable solutions.

The development of virtual manufacturing technologies is mainly driven by demands in the manufacturing industry and their competition on a global market. The voice of the customer is becoming more and more important. Under these conditions a manufacturing system needs to be designed to survive a number of product lifecycles by being flexible in adapting to new conditions. VM constitutes a vital component to manage the development and improvement of complex manufacturing systems under these conditions. Whether such conditions also justify the application of VM in wood industries has not been analysed in this thesis. However, the first barrier to consider is the digital representation of wood and wood processes in the context of VM, or particularly in DES. While there are many methods for the analysis of industrial systems, DES remains the one that gives the highest level of confidence for analysing dynamic processes, i.e. influence of time.

Finally, to enable utilisation of broadband solutions and communication via the Internet for the development of wood manufacturing resources in rural regions, a digital representation of both the product and the plant is a fundamental prerequisite.
8 Final Conclusions and Further Research

In this final chapter, a summary is made of crucial statements established previously in chapter 7. These conclusions are aimed as an outline of primary steps in further research proposed to support the introduction of VM in wood manufacturing industries.

The objective of this work was to answer the question of how and when DES should be applied for the development of a new manufacturing system for wood processing.

It was found that in such a context the need for decision support in the design process is of crucial importance. Efficient development of a manufacturing system also requires involvement of a number of competences from various domains, which emphasizes the need for technical and normative integration. While wood manufacturing industries are generally represented by small and medium-sized firms located in rural regions, lateral and spatial integration are of vital importance and can be supported by VM. It has also been established that wood and wood manufacturing techniques imply specific conditions that are possible to reproduce in a DES model.

Further research should be oriented to enabling a fully integrated virtual manufacturing technology, applicable to conditions of wood manufacturing in small and medium-sized industries.

Continued work in this research field embraces the following areas of primary interest:

- Development of a general information model that addresses the properties of wooden raw material towards a more efficient entering in a DES model
- An analysis of possibilities for improved decision support in the design process of a new manufacturing system, by using DES in the context of other tools within the domain of VM.

This research should be carried out in collaboration with other industrial sectors in pole positions, in order to learn from their experience of the advantages or disadvantages of using VM.

Results from this research are aimed at supporting wood manufacturing industries in their competition on a dynamic market. By developing manufacturing resources in a virtual environment, solutions can be improved, verified and validated, in order to provide better support for decisions to invest in efficiency and flexibility.
9 References

Literature, Articles and Internet sources

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Appendices
Outline of the thesis

The outline of the thesis is illustrated here. It begins with the introduction and reference areas used to define the problem. The centre of the figure shows how the industrial case has influenced the theoretical framework chosen, consisting of 7 areas. The figure also shows that the industrial case covers three chapters; and that analyses and discussion have their own chapter, before the last chapter, which deals with conclusions and further research.
Appendix 2

Overview of the simulation model

The model is shown here from some illustrative perspectives

An overview

Raw material is fed in

Cross-cutting of blocks

Processing of parquet pieces

Blocks are fed to the frame saws by a robot
Appendix 3

Tuning of feed rate and functions

These figures illustrate situations that occurred when trimming the material flow for a unit described by its design in chapter 6.7.

An overview: the glue line and the robot on the right of the picture; pressing, cooling and acclimatisation of glued wood blocks on the left.

The feeding trough to the glue press is too slow, and a bottleneck is developed

The last layer of boards is picked up and stacked by the robot in front of the glue press.
Appendix 4

The wood flooring product

3 layers and their grain direction

Layers glued together and ripped into five boards

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Modelling and Simulation in the Early Stages of the Development Process of a Manufacturing System - A case study of the development process of a wood flooring industry

Författare
Jon Johansson

Sammanfattning
Manufacturing Simulation, or more accurately, Discrete Event Simulation (DES), is an important problem-solving methodology for the solution of many real-world problems in the manufacturing industry. Implementation of DES has become successful in a number of industrial sectors. However, the wood manufacturing industries constitute an industrial sector where DES has still not made a breakthrough. At the same time there is a strong need for development within the sector of the wood manufacturing industries, working with the refinement of, for example, sawn boards into components and consumer products. It can be questioned, why DES cannot be used in these industries?

The objective of this work has been to investigate conditions in the development process of new wood manufacturing systems. This covers the period from when the new system mainly exists as an idea or concept, up to the point when its specifications are finalised. If DES can be integrated in these early development stages, it also highlights an unusual application area of DES, where it is used in the design process. To approach this problem the following references have been used:

general trends and possibilities within the modelling and simulation of manufacturing systems, a technique that is undergoing rapid development.

the unique properties of wood and wood processing that need to be considered in connection with the use of DES......(cont.)