Developing High Performance Manufacturing Systems

Utilising manufacturing system design, strategy and control possibilities for competitiveness in changing environments

A doctoral thesis by
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The work detailed in this dissertation relates to the development of high performance manufacturing systems. The performance factor aimed for is especially flexibility, but there is an intention of making the results adaptable to focus on performance factors of the readers or users' choice. The focus of the presented research is not only to provide means for accomplishing manufacturing that can handle changes but also to accomplish flexibility in another area. The results should be applicable in many different situations.

The research has been divided into three parts: the further development of a manufacturing strategy, the development of a base for a manufacturing system design method and the development of a manufacturing control system.

The developed strategy is called Assembly-Initiated Production (AIP). An implementation of the strategy should provide high manufacturing system flexibility but at the same time contribute to the lowering of inventory levels and lead-times. Different solutions coupled to technical requirements found are also discussed.

The design method research focuses on basic manufacturing system properties and the possibility of expressing these properties by using simple combinable abstract units called concepts. The principle is the same as in physics where real world phenomena may be expressed by using standard concepts as for example time and mass. The intended use of the results is in an early manufacturing system design phase. The method is not directly linked to the AIP strategy, but could be used for implementing it.

Production Planning and Control (PPC) is an important part of a manufacturing system. After having reviewed current PPC practices, a need for a factory floor PPC system working regardless of factory floor layout, was identified. Based on theoretical and industrial studies, the suggested solution is a computerised, decentralised control system, physically separated from the PPC/ERP system. In order to be able to make quick changes in the schedule, to obtain flexibility and to provide the organisation with a tool for manufacturing control and decision-making, the system works in real time to provide accurate and valid data.
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Earlier publications

Results of this work have been published earlier in the following publications:


Results have also been published in other types of reports:


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Introduction
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1.1 Introducing the research area

The history of industry related development contains many interesting and useful pieces of information, also relevant at the present date when it comes to manufacturing system development and improvement.

1.1.1 Manufacturing in general

In the community of manufacturing engineering there are many different ways to design a manufacturing system, to make it work without interruption, to increase its performance and to increase quality. These means are not necessarily directly linked to single manufacturing processes. In this thesis, production is seen as the entire set of operations, manufacturing being included, needed to support the creation of a product. Manufacturing is therefore defined as a subset of production, being the means necessary to manufacture a product. Operation is seen as a general term, meaning to (cause) work, be in action or have an effect. The operations function of the organisation is the arrangement of those resources which are devoted to the production and delivery of its products and services (Slack et al, 2001).

Manufacturing is, as it seems, a subject of an ever-increasing level of complexity. The complexity comes from many different sources, for example:

- Customers: customer demands changing over time in areas like customer specific product variants, demands put on delivery-times, quality of the product etc. These demands tend to change over time.

- Company owners: The demands put on a company to generate profit may change over time.

- Technical issues related to the current manufacturing processes.

- Technical issues related to current product design.

- Human factors involving employees etc.

- Suppliers: Sellers of services, material and components are also companies, subject to the same sources of complexity as the own company.

- Technical innovation: Last but not least, available and non-available technology for the customers to ask for, to improve ones own operations with etc.
These sources of complexity are far from new. Looking at the history of modern industry, one can see that many of the components, today normally associated with modern day production philosophies like Just In Time and Lean Production were under development or available in the mid 19th century (Cammarano, 1997). Notable is the standardisation of operations and product parts as well as the development of product flows through the factories in contrast to the usual department layout. Driving forces behind these ideas were mainly arms manufacturers like Colt and Springfield. One interesting thing to notice here was their simultaneous development of the product and the production. These were not separate issues then, but they became so, possibly because of the increasing level of complexity of production operations. This has again become a hot topic in the form of Concurrent Engineering.

These original ideas about production were used and further developed, most notably by Henry Ford. This was done within the manufacturing of the famous Ford model T in the beginning of nineteen hundreds. Ford has over the years often been used as an example of how not to produce cars; however it would be a mistake not to give Ford credit for much of what we today call a modern way of manufacturing. According to Houndshell (1984), Henry Ford defined mass production as

“Mass-production is not merely quantity production, for this may be had with none of the requisites of mass production. Nor is it merely machine production, which also may exist without any resemblance to mass production. Mass production is the focusing upon a manufacturing project of the principals of power, accuracy, economy, continuity, and speed”.

Many agree that what Ford was missing in this definition were words on long and short-term flexibility. That is also what the Ford production systems lacked and what made the changeover to manufacture another car model after the Model T, so expensive and cumbersome (Andersson et al, 1992). This is a factor that may have been hard to anticipate, mainly originating from the subject of technical innovation and customer demands.

Another issue that usually becomes a point of criticism is the way Ford used to divide tasks among the employees. Since there was a lack of skilled workers, the had to be simple and few for each worker to conduct so that anyone could be employed and instantly put into the production (Andersson et al, 1992). Tasks formed like this usually causes major injuries due to physical wear-out from monotonous long-term operations. The solution of creating simple and repetitive work tasks is becoming more highly topical in industries where there is a shortage of skilled workers as well as where there
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is a need for greater flexibility in hiring and firing personnel, for example within the electronic products manufacturing industry. History seems to repeats itself.

This is also the case when looking at the use of JIT-related ideas and then comparing the 19th century arms industries and Ford with the JIT/Lean Production revolution of the Japanese car industry from approximately 1960 and onwards. The philosophies and ideas of JIT and Lean Production were later, but rather slowly and not entirely, adopted by European and American car manufacturing companies (Womack et al, 1990). One conclusion from looking at the history of modern manufacturing together with the knowledge about JIT and Lean Production is that there are great possibilities to use tried and tested knowledge together with modern technology and company specific solutions, in order to meet and exceed customer demands.

Researching manufacturing solutions, manufacturing related improvement methods and strategies, it is often rather easy to find components originating from the manufacturing industry of the industrial revolution. For example Cammarano (1997) implies this. An interesting study to make is to divide present manufacturing system solutions, found in the industry, into two groups: mere copies and borrowed ideas. One can say that the Toyota Production System (TPS), utilising ideas from the early mass production companies and combining them with current technical solutions and some good ideas of their own, is an example of the second category. If searching for a while, examples from the first category should not be too hard to find. There are numerous examples of implementation of methods used by for example Toyota that have been copied and used at other locations and in other kinds of manufacturing with different levels of success. Toyota does not consider any of the tools or practices such as Kanbans, which so many outsiders have observed and copied, as fundamental to the Toyota Production System. Toyota uses them merely as temporary responses to specific problems that will serve until a better approach is found or conditions change (Spear & Bowen, 1999). If looking deeper into a company that has applied the copying solution as a way of conducting improvement work, one may divide them into two different categories as well: those who know why the copied method is good and how to implement it, understanding the situation, and those who have heard that it is good and therefore have decided to implement it without understanding the situation. The results in the latter case could at best be somewhat random to its nature and at worst, constant failures.
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A key question to ask after having observed this would be:

- What are the key factors that make different solutions successful, given certain variables depending on the situation?

Finding these variables would be of outmost importance.

1.1.2. Means for design and improvement

A quick scan over industrial production related research shows that there are many fields and applications available for designing and improving production related areas. The list of available means would be extensive if printed. In logistics there are, for example methods concerning Supply Chain Management (SCM), where the goals are to accomplish an effective and responsive supply chain by working with everything from information distribution to transportation scheduling. There are more detailed methods available for accomplishing, for example partial goals of SCM. The Kanban control method is one example, used for controlling material flows. In manufacturing in general, there are means ranging from all-embracing ideas like Lean Production to detailed and technical issues like means for aiding in reducing resetting-time, SMED (Shingo, 1985). There are plans for how to create a well working organisation, for instance in the form of the Bionic and Holonic manufacturing philosophies. Product design has many different tools and possibilities like Design For Automatic Assembly, DFA2 (Eskilander, 2001) and product modularisation (among others Pahl & Beitz 1996).

When referred to in general in this thesis, parts of manufacturing systems or entire manufacturing systems that are the results of the use of such methods will be called manufacturing system solutions. For example, the use of cell layouts, the use of the Kanban control method, the use of NC machinery to accomplish a specific goal is seen as a manufacturing system solution. This also includes the combining of such methods; hence using a set of methods also results in a manufacturing system solution.

These means of improvements could be classified according to their nature, for example the level of detail. To be able to label a mean of design or improvement correctly, there are some notions that have to be defined. A common way to classify means for designing or improving manufacturing systems is to divide the means into philosophies, strategies and methods.
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Defining the term philosophy is not easily done since the question of what philosophy is, is a philosophical question in itself. Many sources define philosophy by giving examples of different kinds of philosophical teachings. Such definitions are excluded here, since they tend to leave out the meaning of what a production philosophy really is.

Philosophy is here defined as the use of reason in understanding such things as the nature of reality and existence, the use and limits of knowledge and the principles that govern and influence moral judgement (Cambridge, 2002). Philosophy is a science about principle matters. Studied questions are of fundamental nature (Ekman, 1984). Hence a production philosophy gives fundamental understanding on the nature of specific manufacturing related issues and provides general solution guidelines, sometimes also introducing general ways of system design or improvement.

A general definition of strategy is as a detailed plan for achieving success in situations such as war, politics, business, industry or sport, or the skill of planning for such situations (Cambridge, 2002). It is likely that a production strategy originates from one or more of the production philosophies available, but generally being more detailed. Slack et al (2001) defines a strategy as being more than single decisions; it is the total pattern of the decisions and actions that position the organisation in its environment and that are intended to achieve its long-term goals. They also say that there are many definitions of the term strategy and that there is little agreement on its specific meaning. They define the term operations strategy as being the pattern of strategic decisions and actions, which set the role, objectives, and activities of the operation. As with any type of strategy, one can consider its content and process separately (Slack et al 2001).

- The content of an operations strategy comprises the specific decisions and actions, which set the operations role, objectives and activities.
- The process of operations strategy is the method that it used to make the specific content decisions.

Olhager (2000) shows how the production strategy gives directions for improvement programs in order to support the company’s means of competition.
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Figure 1.1: The production strategy gives directions for improvement programs, making them support the company’s means of competition (Olhager 2000).

The term production strategy is defined somewhat differently than the operations strategy above. The most notable difference is that production strategies do not include the process part, excluding the methods for making strategy content decisions. Instead it is seen as different part of the process of operations improvement, working in conjunction with methods and improvement programs in support of the means of competition.

Definitions of the term method are surprisingly scarce in literature covering manufacturing research. The Swedish National Encyclopaedia dictionary gives the definition; a method is a planned way to accomplish certain results (NE, 2002). According to the Cambridge dictionary (2002) a method is a particular way of doing something, but also an ordered way of doing something. These definitions could be used for understanding the basic task of a method. There are different definitions available that specifies methods used within a specific field. For example, definitions and discussions on scientific methods are readily available, but at the same time, there is a lack of definitions for manufacturing system improvement methods or manufacturing system design methods. A general definition of a design methodology is available form Pahl & Beitz (1996). Design methodology is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains (Pahl & Beitz, 1996). Pahl & Beitz (1996) covers the field design of technical systems. It is however unclear if manufacturing systems are included in the group of technical systems. There are arguments stating that manufacturing systems could, as with any product, be classified as technical systems, but there is still an uncertainty about if it is valid or to what extent it is valid. Therefore this definition is only used as an
example to provide an understanding of what a method is. To conclude the matter of giving an understanding to the meaning of the term method, a simple example is used. Sohlenius et al (2002) provides the example of the machining operation turning in a design related paper. The lathe is the tool; turning is the method and the cutting theory is the scientific theory behind the operation.

The problem one may find is the possible lack of coordination between the different areas in a company when it comes to applying solutions, which encompass the entire production environment. Using inappropriate philosophies, strategies or methods could easily result in sub-optimisations and less than desired improvements, possibly leading to increased costs. To succeed in improving the manufacturing, choosing appropriate methods is of utmost importance, coordinating the use by clarifying what philosophy is applicable and then selecting a strategy accordingly. A strategy could present an overall plan on how the production as a whole should be arranged according to the present demands. It may also specify which methods to use and where.

To be able to accomplish strong means of competition, one has to know how different production areas interact and affect each other as well as what kind of results different changes induce in the entire production, not only to the area being analysed. For example, one has to know how product design changes, made with the goal of creating a product that is easy to manufacture, affect among others the logistics, changes in the Production Planning and Control system, possible changes in the manufacturing layout etc.

This gives another key question:
- How does one find out 1) what to improve or how to design the system and 2) what methods to use when working with manufacturing system development?

This is certainly not an easy question to answer. The possibility that the answer may vary depending on different, possibly unknown, conditions is imminent. Two different areas have to be researched and developed: a general idea of what to do and a methodological approach on how to do it.

1.2 Scope of the research

The initial project definition was rather wide to its nature, consisting of three parts: 1) reviewing and further development of a strategy formulation, 2) the
development of an implementation method and 3) further development of a chosen part of a manufacturing system. These three parts are described more in detail later on. The development of an implementation method was after some time, due to some pre-study results, changed into the development of a manufacturing system design method but with certain delimitations. Manufacturing control (MC) became the chosen manufacturing system part, aiming at the development of an MC system.

1.2.1 Initial aims for the project

As previously identified, one very important factor, needed to succeed in the field of production, is the presence of an overall valid strategy that takes into account future trends, market demands and technological development. Otherwise one will possibly repeat mistakes done by for example Ford, lacking adaptability.

The first phase of the project was focused on the development of the manufacturing strategy and to get an overview of manufacturing related research areas. Therefore, the initial aims are closely related to the strategy research. The overview of manufacturing and its related areas later resulted in more detailed project definitions for the implementation method research and the MC research.

The initial project foundations lie within the ideas generated by current trends in industry, existing Just In Time-philosophies, and the product modularisation method, Modular Function Deployment, MFD (Erixon, 1998). Since more areas were researched and included than just those included in the definition of manufacturing, the strategy was considered to be a production strategy.

With current philosophies and methods as a starting point, the aim was to describe a production strategy with particular focus on assembly. Assembly is an operation that is executed relatively late in the manufacturing chain. Considering that most companies with large product variant numbers desire to give a product its final identity as late as possible in this chain, accomplishing this in the last operation would be a definite achievement. The final assembly is the last of the operations that involves making changes to the product itself and would therefore be the natural choice for creating different variants of products. Rendering the final assembly the point for production initiation is a further advantage.
The main arguments for focusing the strategy design on the assembly process are:

- A growing product variant flora inevitably forces a producer to create them as late as possible in the production sequence. The reasons are administrative, tied-up capital, lead-time, etc.

- The aiming for the shortest possible lead-time to customer creates a lower limit: the time taken to assemble the ordered variant. The only alternative is warehousing, which ties up capital.

The main theme being that the more customer-oriented a company becomes, the greater the need to focus on assembly. The conclusion has been to integrate product development methods such as the MFD method, and effective automatic assembly systems (Onori et al, 1998) into a production strategy, to achieve desired results. A vision built on extreme ideals was the initial foundation for further thinking. This vision is the result of an analysis of current JIT methods and philosophies, and the industrial reality in which they should be applied. The ultimate, visionary goal could be summed up as (Arnström & Gröndahl, 1997):

  - Lead-time from customer order to delivery = 0.

Which gives that:

  - Set-up time/work/costs = 0
  - Capacity shortages = 0
  - Quality shortages/re-work = 0

This vision to be worked upon takes at the same time, the following constraint into account.

  - Capital tied-up in goods = 0

This vision should be interpreted, as manufacturing having to be extremely quick and responsive to be able to deliver to customers since the vision does not allow using stored products to accomplish it. The vision is also very manufacturing oriented. It comes from interpreting demands from customers regarding mass customisation and short delivery-times, and transforming them into a vision concerning manufacturing.

The vision obviously points out that all of the production system features are of primary importance. This includes logistics, which is a vital link in the production chain, as well as set-up times, PPC-systems etc.

These ideal visions are not new. JIT and other philosophies have been
specifically generated for the fulfilment of similar goals. One problem with
the different philosophies is that they do not specify methods for achieving
the goals set up in the descriptions of the philosophy; industry has attempted
to apply JIT since the beginning of the industrial revolution (Cammarano,
1997). However, JIT does not specify methods for achieving or implement-
ing Just In Time delivery, but only states that it is desirable. The manufactur-
ing control method Kanban has been associated with JIT to such an extent
that there are many people in industry that still believe that Kanban and JIT
are the same thing. Such interpretations may lead to negative dynamics: a
failure to use Kanban in a company often produces an opinion, at manage-
ment level, that it will be just as ineffective to incorporate JIT philosophies.
Therefore, in order to avoid such misunderstandings, the part of the project
covering strategy development includes specific methods and descriptions of
method usage.

1.2.2 Objective

Given the description of manufacturing operations and the initial research
goal formulations, the objective is formulated:

The objective of this research is to provide means for accomplishing and
upholding high manufacturing system performance, aiding in the task of
reaching individual company-specific performance goals.

The specific task of accomplishing high performance may vary in way of
execution from case to case. The definition of what is high performance
could be different from case to case. Factors like product and product variant
demand, economical conditions and available technology may change over
time. This calls for the developed methods to be adaptable to different
conditions. Therefore partial research goals were formed, based on this
particular type of adaptability.

1.2.3 Partial goals

Based on the objective and the initial aims of the project, a subset of the
components were chosen for continued research. The subset were then
formed into four different partial goals:
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1. **Study the concept of a strategy based on the initial ideal performance goals and give basic guidelines for explaining the strategy. The details on the ideal performance goals have been presented in section 1.2.1.**

2. **Study what would be needed in the form of technical and organisational means for implementing highly flexible manufacturing in general and based on the developed strategy in particular.**

3. **Develop a general design methodology, aiming at supporting strategy implementation.**

Initially, the goal was to develop a method for implementation of the developed strategy. The problem with that goal is that the strategy may not always be sound, depending on numerous factors, some being extremely hard to anticipate. If the strategy would not be used, the developed method would be useless as well. For example, the prerequisites for the strategy implementation and use could change overnight. To make the method less dependent on the strategy and therefore aiming for results useful in a wider context, the research was instead focused on developing a method useful when implementing any strategy. The change of formulation does not change the intention of the method being useful when implementing the strategy developed in the research project. This change of intentions was made when approximately half of the strategy research had been conducted.

During the initial studies aimed at strategy development, the production planning and control (PPC) function was identified to be of outmost importance for accomplishing high performance manufacturing. It is also an area leaving many challenges and possibilities for improvement. The research area was though mainly chosen because of the special interest of the author of this thesis. PPC functions are available at many levels in a company. The area of Supply Chain Management (SCM) includes PPC functions, many times focusing on the transportation of material and components to and from a factory. Manufacturing control (MC) on the factory floor is another well-known research area, involving discussions on Just In Time, the Kanban control method etc. PPC could also be divided into long term planning, short term planning and reacting to events without any planning, giving it a time dimension in addition to the geographical dimension. This wide definition of PPC has been researched during the early phases of the project, in the sense of it causing implications on the manufacturing operation as a whole.

The area chosen for research is the one of factory floor manufacturing control.

4. **The fourth research goal is to provide means for performance improve-**
ment possibilities in manufacturing by introducing a new MC method, focusing on acting on events and therefore leaving out planning issues.

To accomplish solutions to these goals, lower level goals were emerging over time during the project. To fully explain them requires a considerable amount of information to be introduced. Therefore these goals are presented in the chapters, in vicinity to the related research.

Figure 1.2: The objective and research goal structure of the research presented in this thesis.

The relations between different research goals and the objective are presented in figure 1.2. In the figure it is shown where lower level partial goals are defined in detail.

1.3 Delimitations

1.3.1 A general delimitation

No economical evaluations, for example cost calculations, have been included in the developed methods and theories. Economical factors have however, always been present as a factor in the research work. Therefore
could for example, cost calculations be carried out in parallel, when using the resulting proposed methods. The major reason for excluding economical calculations was mainly the problem with prices, costs, incomes etc, fluctuating over time. It could cause the results to be useless in a short time. There is also the assumption that working with the suggested solutions does not create a need for anything new in the field of making economical calculations. Presently available methods would most likely do in this task.

1.3.2 Delimitations specific to the proposed design method

The manufacturing system design method is developed to be used in an early system design phase. Why and how this is accomplished is described more in detail in the chapters 4, 5 and 6. It is however of outmost importance for the quality and outcome of the research and it is therefore appropriate to mention it in the delimitations section.

Since the method is to be used in an early design phase, the outcome of its usage, the first manufacturing system model, is planned to be improved at a later stage. Hence, the suggested method is not supposed to give a 100% accurate manufacturing system solution. It is to be a tool for designing a first solution, a task that has been identified as a valid research area.

The suggested method is focused on manufacturing processes and the way the processes have influences on surrounding processes and at a later stage, the entire manufacturing system. A very important function in production is the delivery of material and parts. The proposed method is not intended for using when designing such logistics systems. The need for such systems are however identified and argued for in practice in chapter 3 and in theory also in chapter 4. Lack of material is also included as a parameter in the proposed design method. Designing a logistics system is also assumed to be a process following the draft of a first manufacturing system design, making it an issue of later design phases.

Because of constraint in time available to the project, the method will not be entirely complete. Some additional work has to be done for accomplishing a tested working method. Mainly it includes full testing of the method at real cases and the further development of the information handling in the method. More exact descriptions on this are available in chapter 6.
1.3.3 Delimitations specific to the proposed control method

As mentioned earlier, the intended research area is factory floor manufacturing control, excluding control of processes outside the factory. This does not mean that the method could not be used in that sense, but it has to be investigated further. Therefore the research is geographically limited to a factory or a plant.

The intention with the method is to provide means for manufacturing control hence planning is excluded. There are other methods available for production planning, which often are well established within a company in the form of ERP software modules. Therefore long and short term planning is left out and the focus is on reacting on events.
1.4 Disposition

The thesis is structured in order to make the information as accessible as possible to the reader. This means that there is a difference between the order of the material presented and the chronological order in which the research has been performed.

Figure 1.3: The structure of the thesis with the chronological order in which the research has been performed. The chapters are marked as numbers within the squares and the chain of argumentation is marked as arrows. Chapter 8 and 9 are excluded for practical reasons.

As one can see, there is some overlap when it comes to when certain parts of the research has been conducted.
Chapter 1 includes an introduction to the research area and general arguments on why the research has been performed as well as the research goals. The structure of the thesis is explained and publications made by the author of this thesis are presented. The relevance of the publications is described in relation to the different chapters of this thesis.

Chapter 2 contains explanations of research related aspects. The scientific methods used are explained, as well as a general view on management related science and scientific methods. Certain delimitations are made.

Chapter 3 is the presentation of the developed strategy named Assembly-Initiated Production (AIP) and covers research goal number 1 and 2. This chapter also contains a critical review of the strategy and the related research.

Chapter 4 is used for introducing and explaining theory being central building blocks, used in the proposed design method.

Chapter 5 is closely related to chapter 4, providing ground for using the theoretical material in a more practical manner. Chapter 4 and 5 covers research goal number 3. Chapter 4 topics were researched in parallel to and after chapter 5 topics, mainly because the need for the content in chapter 4 was not recognised until the work with the structure had begun.

Chapter 6 is used for presenting the final results in a more condensed manner, containing a step-by-step type of instruction. This chapter could also be used for quick reading, when knowing about the research is of less importance than understanding the methodological approach. One should note that if reading chapter 6 only, most of the details about the strategy specific research presented in chapter 3 would be missed. Chapter 6 also contains a critical review of the proposed design method.

Chapter 7 contains guidelines for the development of a chosen technical system, hence covering research goal number 4. Detailed directions in how to design a production planning and control system for use on the factory floor are given. Chapter 7 also includes a critical review of the resulting MC system.

Chapter 8 is the critical review and future research chapter. Since the different research parts have been reviewed in their part of the thesis respectively, this critical review is focused on general research aspects concerning the project as a whole. Since chapter 8 is related to all the other chapters, it is not included in figure 1.2.

Chapter 9 contains references.
Chapter 1

1.5 Previous research

To show relevance of earlier publications, research papers presented at scientific conferences or published in journals are put into context, relating them to the chapters in this thesis. In the papers, the content of the chapters are presented in part or as a whole.

Figure 1.4: The author’s previous publications in relation to the chapters of the thesis.
Introduction

Strategy related research

Presenting AIP, putting AIP into a research and industrial context and establishing essential AIP related demands and principles.


Licentiate thesis

Presenting the AIP strategy, applicable technical and organisational solutions. The first draft of an implementation methodology was also presented.


Forming the design methodology

The basic principles, theories and theoretical definitions were presented.


Chapter 1

Factory floor manufacturing control

The research regarding manufacturing control (MC) system design was presented. The emphasis was put on defining basic information units and examining different MC methods in order to find basic components that cause desired properties obtainable by using certain methods. The first drafts of the design guidelines were also presented.


Journal articles

Larger parts of the project were presented. AIP is presented in the first article [9] and information retrieval, handling and use in environments with short lead-times in the other [10].


Introduction
Chapter 1
Research approach

2

Research approach
Chapter 2

2.1 Conducting research focused on manufacturing

When going through literature covering research methods for use within scientific studies of management, manufacturing and logistics, one can see that research within these fields are heavily dependent on the knowledge of the researcher or the research team. This is very much due to the nature of related studies, which often has to cover large and complex systems, involving many uncertainties originating from many different sources. The research object may often include people and therefore a social system that makes the studies leaning towards an approach, similar to the one of behavioural studies. Such studies are more of a qualitative nature than a quantitative. Qualitative research and methods have the distinguished feature of unknown possible solutions and results (Gunnarsson, 2002). One could easily argue that such is often the nature of research projects within the field of industrial management.

Gunnarsson (2002) also states that an advantage the qualitative approach has over the quantitative approach is that the qualitative approach considers the entirety in a way not possible in quantitative research. Quantitative methods on the other hand, have the advantage of giving an objective measurement of the probability of the truth of the result. Qualitative research methods often contain for example, interviews and observations and it is possible that the researcher has to change methods during the project during its implementation (Gunnarsson, 2002). The goals with the study are usually not about number, distributions or exact measurements, more like presenting new aspects related to a problem. In a qualitative research project, forming details about which methods to use ahead of the defining of problem and cause with the study, is an incorrect way of procedure.

The research presented in this thesis is predominantly results from a qualitative research approach. In some segments where single questions had to be answered or where the questions could be formulated as theories, a quantitative approach was chosen.

As stated earlier, industrial management research relies heavily on the knowledge of the researcher. Gummesson (1991) divides a researchers knowledge into understanding and preunderstanding. Preunderstanding refers to such things as people’s knowledge, insight and experience before they engage in a research project. Preunderstanding also implies a certain
attitude and a commitment on the part of the researcher. It involves their personal experience as an essential element in the process of collecting and analysing data. Gummesson (1991) also points out the importance of using the preunderstanding, but not to be its slave. This means that one should have a solid base of preunderstanding, but at the same time, have an open attitude and if needed, change point of view and review the knowledge base that forms the preunderstanding. It is essential that the preunderstanding is subject to change and that the researcher is aware of paradigm, selective perception and his/her own personal defence mechanisms.

Understanding refers to the knowledge that develops during the program or assignment. The understanding is dependent on the preunderstanding, since it affects the experience and involvement that leads to understanding.

Figure 2.1: The development of understanding from preunderstanding. This figure is the result from putting two figures, originally available in Gummesson (1991), together into one.
Chapter 2

One should note that the achieved understanding becomes preunderstanding in the next phase of a larger research project. Chalmers (1995) points out that observations are dependent upon the theoretical knowledge of the observer and therefore it is very important to have the correct theoretical background before conducting empirical research.

Why this is the case is more understandable when analysing figure 2.1 which shows that both preunderstanding and understanding are partly dependent on the experience of others, acquired via literature and other sources.

The research presented in this thesis is aiming at the practical applicability of results. To get consistency between theoretical models and observations, a dual scientific procedure may be used. Such a model, described by Jørgensen (1992) combines a practical, problem based and a theory based approach (fig 2.2).

![Diagram of the dual scientific procedure](Image)

**Figure 2.2: A procedure for applied research in which attention is given on the interaction between theory and practice (Andreasen, 1998 based on Jørgensen, 1992).**

The original reference, Jørgensen (1992), has not been found. The Jørgensen (1992) material is available in Andreasen (1998).
Research approach

The research presented in this thesis aims at following this approach where the practical area consists of applied research and the theoretical area, of theoretical research. Jörgensen (1992) describes the process of research as an ongoing iterative process of analysis and synthesis in these areas.

Applied research focuses on observation, modeling and analysis of existing things. Results can be directly used in practical applications.

Theoretical research concerns development of new concepts based on scientific knowledge. Results are new knowledge, which can be used for practical applications.

Analysis refers to the ability to break down material into its component parts so that its organisational structure may be understood. This may include the identification of the parts, analysis of the relationships between parts, and recognition of the organisational principles involved. Learning outcomes here represent a higher intellectual level than comprehension and application because they require an understanding of both the content and the structural form of the material.

Synthesis refers to the ability to put parts together to form a new whole. This may involve the production of a unique communication (theme of speech), a plan of operations (research proposal), or a set of abstract relations (scheme for classifying information). Learning outcomes in this area stress creative behaviors, with major emphasis on the formulation of new patterns or structures.

In applied research, the research problems, the methods used and the research material are closely linked and are affecting each other in different ways. For example, the methods used may affect the results in several ways. This could be directly to the results or by influencing the data (Ejvegård, 1991). Figure 2.3 shows the influences different factors may have on the research result.
Chapter 2

Figure 2.3: The methods affect the research result in several ways (Ejvegård, 1991)

The figure is to interpreted as:
1. The choice of research problem affects the result.
2. The choice of research material affects the result.
3. The choice of research material affects the method.
4. The choice of method affects the result.
5. The choice of method affects the data.

Since both the fact that an observation is dependent on the observers experience and knowledge, together with the results dependence on the methods used, it is very important to have the correct theoretical foundation and to choose the right methods for the research. Otherwise the results may be corrupt.

To accomplish scientifically sound research work, this pattern of interference has to be taken into account and dealt with. The research structure should be designed with this in mind. As a mean of research quality assurance, the work should also be well and clearly documented. Quality related issues are described in chapter section 2.3. Gummesson (1991) proposes five types of preunderstanding, knowledge and personal characteristic which are essential in order to fully understand processes in an organisation. Applying them would increase the understanding of the phenomenon described in figure 2.3. The five types are:

- Knowledge of theories. Theories include concepts, models and approaches, helps to identify, diagnose, define and analyse major factors and relationships.
- Knowledge of techniques. This type of knowledge comprises techniques,
Research approach

methods and actual tools of operation such as the use of computer programs, knowledge required to plan, execute and analyse research projects etc. Absence of knowledge of techniques will result time-consuming operations and lack of focus.

- Knowledge of institutional conditions. This category includes knowledge of technical conditions, customary practice, key decision makers and other specific mechanisms and factors relating to particular industry, company, market, product, service etc. This is a highly detailed type of knowledge that is acquired mainly through experience.

- An understanding of social patterns. Each company creates its own cultural value system of rules of corporation, social intercourse, communication etc. It could be very difficult for a researcher to gain an in depth understanding of the social patterns within a company that is new to them.

- Personal attributes. Consideration must be given to the researchers personality, which in many instances will prove to be of great importance to the outcome of the project.

For the procedure of development of understanding to result in correct, valid and applicable results, a number of issues related to science and the use of scientific methods have to be taken into account. In the next section of this chapter, relevant scientific issues of a more practical nature, related to the conducted research, are discussed.

2.2 Methods used

2.2.1 Terminology used for describing reality

A first step in the process of deciding upon suitable parameters for using when describing the world covered in this thesis is to introduce, specify and define basic expressions that are appropriate for describing and modelling manufacturing. The basic expressions used are concepts, laws and principles, models, theories and units. A physicist could use them as a base for presenting her or his view of a situation, an experiment or whatever is needed since they are common expressions in physics, used to describe events and phenomena in a specified environment.
Chapter 2

Concepts
A concept is an idea or a physical quantity that is used to analyse natural phenomena. For example, the abstract idea of space is a concept and so is the measurable physical quantities length, time, acceleration, force etc (Benson, 1991). McGill & King (1989) states that there are several concepts that are primitives in the study of mechanics. Space, time, force and mass are stated. In this research, the term concept is used when discussing parts forming manufacturing systems, most often when discussing manufacturing system design. The concepts are defined as similar in nature to those used in the field of physics.

Laws and principles
A principle is a very general statement about how nature operates. It spans the whole subject and is part of its foundation. Laws are usually more specific, using mathematics to describe relationships. Sometimes, the terms law and principle are used interchangeably (Benson, 1991). Newton’s laws are well known and often used. However, they do not apply for example, when velocities approach the speed of light. That is, the laws are only valid in certain special frames of reference (McGill & King, 1989). The fact that laws only are valid in a certain frame of reference, should also apply to manufacturing research. In the research presented in this thesis, the frame of reference is available, mainly in chapter 1 but also in chapter 4. Certain conditions are also pointed out when necessary, when it is important to do so. Finding and expressing laws, accurate enough for use within the stated frame of reference is important for the presented research work, and is therefore also an important part of this chapter.

Models
A model is a convenient analogue or representation of a physical system. The phenomena occurring in the system are analysed as if the system were designed according to the model. A model may merely replace the real thing to simplify the analysis. A model is often a mental picture of the structure or working of a system. There are also purely mathematical models whose mathematical properties reflect those of the real system. There are definitions of mathematical models, stating that such models are used when describing properties in an exact manner (Benson, 1991). One could argue that there are mathematical model that do not describe properties exactly but they are considered accurate enough. Statistical models are of such nature.

A model could be a useful tool, even if it is incomplete or later proven to be incorrect (Benson, 1991). The possibilities when creating models are plentiful. Creating a model of the manufacturing system is a part of the proposed
Research approach

method and chapter 5 is dedicated to the creation of a simple, yet useful model structure.

Theories
A theory uses a combination of principles, a model and initial assumptions. Theories are often encountered in scientific work. A theory, believed to be correct, may after a long time, be falsified or improved. A theory can only describe a natural phenomenon, not explain it. Theories do not necessarily follow from experimental observations (Benson, 1991), they may have different kinds of origin. Theories are used extensively in this thesis and are explained and argued for accordingly.

Units and dimensions
The value of any physical quantity must be expressed in terms of some standard or unit. For example, the distance between two points could be measured in meters. All physical quantities can be expressed in terms of three fundamental quantities: mass, length and time. It is often convenient to define additional base units. In physics, the units for temperature and electrical current are considered as such (Benson, 1991).

2.2.2 Obtaining and analysing theoretical data

An important part of scientific research is finding relevant and scientifically proof literature. Scientific papers and books have been searched for using library catalogues, bibliographic databases, full text E-journals, other journals and the Internet.

When conducting searches for literature the guidelines on searching for and finding scientific information by Kihlén & Lantz (2002) have been used as well as information given by the Royal Institute of Technology Library (KTHB, 2002). Additional information on searching the Internet, mainly focused on strengths and weaknesses of different types of search-engines was provided by KTHB (2002).

Analysis of important written material has been reviewed according to scientific systems called complete analysis described by Björnsson et al (1994). In a complete analysis one structures important conclusions, problem description and argumentation into one descriptive and one valuing part. The descriptive part consists of an interpretation of which arguments that have been used and how they are structured. The chain of argumentation is put together. In the valuing part, one looks at the structure of arguments and
values the strength of the entire argumentation. The primary reason for using complete analysis is to have a structured approach for reviewing material and to help creative thinking instead of just accepting the written conclusions. Complete analysis has been used to establish a chain of evidence and explanation building in read as well as written material.

There are possible dangers of only conducting theoretical studies. According to Gummesson, (1991) the researcher runs the risk of entering a vicious circle of academic research, where researchers quote each other without adding new, consistently tested material, which may lead to inaccurate results. Another risk is that one may miss a lot of facts or misunderstand facts if practical experience is lacking, risking the deduction of incorrect conclusions. This is made clear by looking at figures 2.1 and 2.2 that show the interactive process of industrial and theoretical research. To avoid this to as large extent as possible, theoretical studies has been combined with industrial studies.

2.2.3 Methods used for industrial studies

Choosing the appropriate strategy for research work, conducted in a manufacturing environment has been done according to the specific problem nature of the research problems. The form of the research question provides important leads to which research strategy to use (Yin, 1994). Different strategies may overlap in usability though. Yin (1994) has compiled a list of strategies and their appropriate use.
Research approach

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Form of research question</th>
<th>Requires control over behavioural events?</th>
<th>Focuses on contemporary events?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>how, why</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Survey</td>
<td>who, what, where, how many, how much</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Archival analysis</td>
<td>who, what, where, how many, how much</td>
<td>no</td>
<td>yes/no</td>
</tr>
<tr>
<td>History</td>
<td>how, why</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Case study</td>
<td>how, why</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Figure 2.4: Choosing a research strategy based on the nature of the problem (Yin, 1994).

The strategies used in the AIP related research have mainly been surveys and case studies. Parts of the Axiomatic Design method have been used on occasion. An overview of the strategies and methods follows. Details about how the strategies have been implemented and about the use of the methods are presented in conjunction to the presentations of the research in following chapters.

Case studies

Case study research strategy is used when researching few objects for numerous considerations. A case study is an empirical study that investigates a contemporary phenomenon within its real-life context when the boundaries between the phenomenon and context are not clearly evident and in which multiple sources of evidence are used.

An important advantage with case study research is the opportunity for a holistic view of a process (Gummesson, 1991). That is to enable the researcher to study many different aspects, examine them in relation to each other, view the process within its total environment and also utilise the researchers theoretical knowledge and understanding.
Chapter 2

The case studies are the preferred strategy when (1) “how” or “why” questions are being posed, (2) when the investigator has little control over events and (3) when the focus is on a contemporary phenomenon within some real-life context (Yin, 1994). All three situations are valid in the case studies conducted within this thesis.

Sources to a case study are not limited to qualitative research, quantitative methods could be used as well (Yin, 1994). The nature of a case study could also be of either quantitative or qualitative nature. A quantitative case study tests a theory while a qualitative case study creates theories (Merriam, 1994). In this project, the case study strategy has been used with both intents.

Main sources of information in the conducted case studies have been documentation (research papers, books, manuals, internal reports etc), interviews (with technical and management personnel) and direct observations (industrial studies).

Surveys

Surveys include structured interviews and written questionnaires. The goals with the surveys have been more general and the sought answers of a wider nature than with the case studies. Generally, surveys preceded case studies so that more precise research questions could be asked.

Figure 2.5: The combined use of surveys and case studies.
Research approach

Subjects for the surveys have been persons with technical and management related knowledge. The questions were of the nature of the ones presented in figure 2.4. The intentions were to obtain a general view on manufacturing related problems to be able to form more specific research questions. Interviews and questionnaires were complemented with literature research. The process of using combinations of surveys and case studies was used when entering new research areas.

Axiomatic design

Axiomatic Design (AxD) is a design method that addresses the internal relationship of a design and applies a probabilistic view of design. A comprehensive presentation of AxD is available in Suh (1990), but the original theories by Suh are of earlier origin.

AxD puts the function of the product to be designed, in focus. The ultimate goal of AxD is to establish a scientific basis for design and design activity improvement by providing the user with a theoretical foundation, based on logical and rational thought processes and tools.

![Diagram of the four domains in the Design World](image)

*Figure 2.6: The four domains in the Design World (Suh, 1990).*
Chapter 2

In AxD design objectives are formed through the establishment of Functional Requirements (FR) and Constraints (C). The establishment of FRs comes from customer demands. FRs are a minimum set of independent requirements that completely characterize the functional needs of the product. Constraints are bounds on acceptable solutions and are divided into two types: input constraints and system constraints. Input constraints come from the design specification and system constraints are imposed by the system in which the design solution must function. FRs results in design parameters (DP), which contains a strategic choice to fulfil the related FR. DPs are usually nouns. A DP results in an activity, a process variable (PV).

AxD states two design axioms that assist in the work to make the right decision when choosing between different design concepts. The axioms also assist in the quality evaluation of proposed solutions.

The rules of Axiomatic Design states that objects should be independent or uncoupled (Axiom 1) and the best design is the one with the lowest information content (Axiom 2).

Axiom 1: Maintain the independence of the functional requirements (FR). FRs are established from the needs identified and put on the product to be designed. FRs are defined as the minimum set of independent requirements that the design must satisfy. Axiom 1 states that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs. An important issue is that Axiom 1 is about functional independence, not physical independence. That is: the functions should be independent. Physical integration of functions could be desirable as long as the functions remain independent.

Axiom 2: Minimize the information content of the design. Axiom 2 is also called the Information Axiom. It provides a quantitative measure of the merits of a given design and is therefore useful in selecting the solution most likely to be successful among acceptable solutions. Hence, Axiom 2 is about the statistical probability of success and would practically be dependent of for example, tolerances and variations in manufacturing processes. Axiom 2 states that a solution with less information content than another, is a better solution since it has a greater probability of success.

An important aspect of AxD is the separation of problems from means on how to solve them.
Concluding words on methods used

One can conclude that the research presented in this thesis is based upon industrial studies, complemented by theoretical studies to create a solid theoretical foundation as a starting point for, and to be able to come to correct conclusions about, the industrial studies.

The research work has been conducted as:

- Study of literature to discover and understand available theories, methods, phenomena and tools. Literature includes books about related subjects, research papers, articles in scientific journals, articles in other printed media and Internet. The information obtained has been used according to its scientific value. Consequently no information that has not been scientifically proven has been used to scientifically prove theories.

- Discussions and interviews with people in positions covering the entire spectrum of production within companies with production in Sweden. The goals have been to identify, understand and define production related research problems.

- Industrial studies to understand the behaviour of manufacturing systems, including interviews and observations.

- Industrial studies to examine a certain phenomenon within a company and the company’s relationship to its customers and suppliers, commonly called supply chain.

- A constant review of the theoretical knowledge about the situations studied in the industry to be able to interpret the observations made in the industrial studies and the information obtained in interviews and discussions.

The constant reviewing makes the use of these methods constant, ongoing processes in opposite to using the methods one at a time and only once.

2.3 Research validity and reliability

When discussing the quality of research, the terms validity and reliability are often used. Validity refers to the extent to which the researcher is able to use his/hers method to study what is intended, that the used method or strategy is
suitable for the task. Reliability refers to the possibility to repeat the research and end up with identical results (Yin, 1994).

Validity and reliability of qualitative research, could be divided into:

- Inner validity or credibility (Gunnarsson, 2002): reflects the researchers ability to explain how the research process affects the results.

- Objectivity of conformability (Gunnarsson, 2002): similar to inner validity and reflects the researchers ability to remain neutral and unbiased towards the data.

- Internal validity (Yin, 1994) establishing a casual relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships. This is an issue for explanatory case studies where one tries to determine why a certain event leads to another specific event.

- Construct validity (Yin, 1994): establishing correct operational measures for the concepts being studied.

- External validity or transferability (Yin, 1994; Gunnarsson, 2002): establishing the domain to which a study’s findings can be generalised. In quantitative research, the researcher defines the transferability and provides means for the reader to agree or disagree. In qualitative research, the reader decides the transferability through the presentations made by the researcher.

- Reliability or dependability (Yin, 1994; Gunnarsson, 2002): demonstrating that the operations of a study, such as the data collection procedures can be repeated with the same results.

Generally, reliability is strengthened through clarification of the point of views, backgrounds, theoretical perspectives etc, which is behind the research as well at the path to the conclusions. To ensure a high research quality, Yin (1994) suggests certain tactics, here presented in figure 2.6.
Research approach

<table>
<thead>
<tr>
<th>Tests</th>
<th>Case study tactic</th>
<th>Phase of research in which tactic occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construct validity</td>
<td>- Use multiple sources of evidence.</td>
<td>- Data collection.</td>
</tr>
<tr>
<td></td>
<td>- Establish chain of evidence.</td>
<td>- Data collection.</td>
</tr>
<tr>
<td></td>
<td>- Have key informants review draft case study report.</td>
<td>- Composition.</td>
</tr>
<tr>
<td>Internal validity</td>
<td>- Do pattern-matching.</td>
<td>- Data analysis.</td>
</tr>
<tr>
<td></td>
<td>- Do explanation-building</td>
<td>- Data analysis.</td>
</tr>
<tr>
<td></td>
<td>- Do time series analysis.</td>
<td>- Data analysis.</td>
</tr>
<tr>
<td>External validity</td>
<td>- Use replication logic in multiple-case studies.</td>
<td>- Research design.</td>
</tr>
<tr>
<td>Reliability</td>
<td>- Use case study protocol.</td>
<td>- Data collection.</td>
</tr>
<tr>
<td></td>
<td>- Develop case study data base.</td>
<td>- Data collection.</td>
</tr>
</tbody>
</table>

Figure 2.7: Case study tactics for ensuring research quality (Yin, 1994).

Gunnarsson (2002) does not suggest specific action for ensuring research quality but mentions triangulation as one important way of strengthening a study design. Triangulation means using combination of methodologies in the study of the same phenomena or programs. Merriam (1988) mentions triangulation as a way of strengthening inner validity. Patton (1990) mentions four basic types of triangulation:

1. Data triangulation. The use of a variety of data sources in a study.
2. Investigator triangulation. The use of several different researchers or evaluators.
3. Theory triangulation. The use of multiple perspectives to interpret a single set of data.
4. Methodological triangulation. The use of multiple methods to study a single problem or program.

Details about how the presented strategies have been implemented, about the use of the methods as well as measures to ensure research quality are presented in conjunction to the presentations of the research in following chapters.
Chapter 2
Results part 1
Assembly-Initiated Production
3 Assembly-Initiated Production
Chapter 3

In this chapter, the part of the project aiming for the development of a production strategy is presented. The base is a number of industrial surveys and case studies conducted over a period of approximately three years and involving participants representing 19 companies active in Sweden. The representatives have provided knowledge by participating in interviews and project meetings. 10 of the companies have been subjects to case studies at location, visiting their factories for different purposes.

3.1 Assembly-Initiated Production fundamentals

Assembly-Initiated Production (AIP) is classified as a strategy according to the definitions of the term strategy, presented in chapter 1. It is a detailed plan on how to accomplish flexible manufacturing in the terms of introducing new products, introducing new product variants and being able to handle shifting volumes. It gives directions for manufacturing system design and improvement programs, supporting the company’s means of competition when the described flexibilities are of utmost importance.

The strategy AIP is based on the Just In Time philosophy and related methods, aiming for short delivery times, and therefore also short internal lead times. Since short lead times often is the same as secure lead times, it is of great importance to work on lead-time reduction (Wilson, 1997).

Trends that have been identified as important factors to be considered when developing AIP are (Karlsson & Onori, 2000):

- Shifting production volumes, having to ramp up and down very quickly in response to the order volumes (large capacity fluctuations).
- Shorter product life spans (frequent system reconfigurations).
- High, and continuously increasing number of product variants.
- Just In Time-delivery.

These trends put different requirements on the companies and their production. The AIP strategy is therefore developed to take these factors into account and to do this comprehensively, it has to include all areas involved in the production.
This gives the definition of AIP being a strategy with:

- A focus on JIT related parameters.
- An assemble to order manufacturing environment.
- Reconfigurable manufacturing systems. For example there is the need for stepwise expandability and the possibility to adapt to different products (Onori et al, 1999).
- Product designs that assist the production processes and, at the same time, result in products attractive to customers. Example of solutions is product modularisation and standardisation of parts, both which are specified as being parts of the AIP strategy.
- Information systems that are designed to support the processes. This means that the information systems themselves have to be reconfigurable in the same manner as the processes.

To accomplish an AIP implementation, there are other areas that have to be considered. This means that they have to be developed in accordance to AIP goals. Closely related to the definition but not specifically included are:

- A supply chain that supports the manufacturing processes and that strengthen the production as a whole.
- Competent and flexible personnel to enhance the characteristics of the rest of the production system. They must have the ability identify different situation and to react in a suitable way.
- Other personal related subjects like for example human-machine interfaces, working environmental issues, has to be taken into account when creating the system.

As one can see, AIP has to be developed in line with issues, normally associated with mass customisation. Mass customisation emerged as manufacturers, enabled by their proficient Lean Production systems, explored ways to better meet the need of customers (Alford et al, 2000). Going from mass production to mass customisation could require a total reengineering of the company. A reengineering is basically enacting multidimensional change to achieve dramatic improvements in performance. To be fully capable of supplying unique goods and services to customers as a planned strategy without sacrificing cost control, product quality or delivery speed, companies must actively redesign business processes for the era of mass customisation (Gilmore, 1993). AIP has since the start, been a strategy with roots in JIT and Lean Production with the goals of satisfying a large number
of customer needs. It therefore intends to be a practical strategy for mass customisation.

When the AIP research work was started, the basic definition of AIP was already present (the definition is available in section 1.1). Therefore the research goals covering strategy development was not to develop a new theory but to further develop and exploit the possibilities of an existing one. The first partial goals were:

A) To clarify whether there exists a set of basic constraints, which must be satisfied prior to the implementation of an AIP-based system.

B) To pinpoint the driving factors which influence the performance of AIP. These may subsequently be used to form an implementation and evaluation method for AIP.

C) To present a first draft of such a method. The proposed method will not be tested in this project and will likely require some rework to be entirely useful in the intended ways. This will be considered as future research.

These partial goals are to be considered second level partial goals, related to the strategy development goals presented in section 1.2.3 and are shown in figure 1.2 as research goal A to C.

3.2 Describing the AIP structure

3.2.1 Entry points in the manufacturing flow

The placement of Custom Order Entry Point (COEP) and Order Specification Entry Point (OSEP) are central issues in the definition of AIP. Bikker and Dekkers (1994) describe the two points as:

COEP: The point where an order penetrates into the hardware flow, the Custom Order Entry Point determines which specific activities have to be undertaken after the start of a custom order.

OSEP: The position of the Order Specification Entry Point indicates the amount of engineering work before any order is specified for ‘production engineering’. The more the design and configuration has been developed in advance, the less the amount of engineering work that remains to be done for processing a specific order.
Assembly-Initiated Production

The choice of a specific OSEP does not necessarily indicate the use of a specific COEP or vice versa (Bikker & Dekkers, 1994).

![Diagram of different manufacturing methods](image)

*Figure 3.1: Creating different manufacture to order and manufacture on prognosis situations by shifting the Order Penetration Point (the figure was originally taken from Stake, 2001b).*

Figure 3.1 shows different ways of manufacturing based on the Order Penetration Point (OPP). The OPP defines the stage in the manufacturing value chain where a particular product is linked to a specific customer order (Olhager, 2001). If the OPP is close to the supplier, the amount of work to be done after receiving an order, will be done with less dependence on a prognosis, but will result in longer delivery-times. If the production will be arranged with the OPP closer to the customer, the delivery-times will be shorter but the production will be more dependent on prognosis, especially if the lead-times through the production are long. Therefore, if the prognosis is incorrect, the sought after product might not be available and the delivery-time becomes as long as in the case of engineer to order. The storage of finished products will also cause larger costs for capital tied up in goods, with make to stock being the other end of scale.
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![Diagram of a simple production chain](image)

**Figure 3.2: A simple production chain. After Bikker & Dekkers (1994).**

Figure 3.2 is a re-interpretation of fig 3.1, for a simple production chain, with 1 being make to stock, 2 assemble to order, 3 manufacture to order and 4 being engineer to order.

The extreme here is engineer to order. This means placing the COEP and OSEP early in the production chain (in this case, 4). In the other end, there is make to stock (1). Usually, make to stock means placing the COEP early and the OSEP late in the chain. Placing the COEP early usually is undesired. Custom orders are usually necessary because one cannot satisfy customer demands with standard product. Having an early placed COEP means long delivery-times on such orders.

The basic idea with AIP is to assemble to order, placing the OPP in position #2. This means shifting the OPP forward, compared to make to order or shifting the OPP backwards compared to make to stock. According to Olhager (2001), reasons for forward shifting are to:

- Reduce the customer lead-time.
- Improved manufacturing efficiency.

But there are also negative effects (Olhager, 2001):

- Relying more on forecasts.
- Reduce product customisation.
- Increase work in process.

These problems could be dealt with by using backwards shifting, but are
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primarily intended to be dealt with in the AIP strategy, by using technical and organisational manufacturing system solutions.

In the AIP strategy the COEP is also placed at #2, assemble to order. To satisfy all customers, the OSEP should be placed in the final assembly as well. This means that customer specific products as well as standard products could be manufactured and delivered in a short period of time.

This is done by using modularised products and standardised parts, according to the idea to assemble a large number of product variants by combining a few variants of standardised components and modules. Therefore the manufacturing, up to the final assembly, should be the manufacturing of product modules and standardised parts. This makes the need for engineering activities less common since the customer demands can be satisfied, basically with a few manufactured standard product variants. The individual product variant creation will be done in the last operation that makes changes to the product, the final assembly.

With AIP, the total delivery-time will be the time to assemble and package the products plus the shipping time to the customer and gives the possibility to eliminate storage of finished products. The delivery-time will arguably be longer than if finished products would be stored though, but only if the sought after products actually are available in the storage facility. If they were not, the delivery-time would at best be the total manufacturing lead-time.

3.2.2 Forming an Assembly-Initiated Production structure

As stated, the AIP approach describes how the customer order should be placed directly within the final assembly of the product, and offers suggestions as to how a modularised assembly factory leads to shorter lead-times (Erixon, 1998), a variant creation point within assembly (not within parts manufacturing or design) and faster ramp-up times.
Figure 3.3: The AIP structure modified from Karlsson (2000a). Solid arrows show hardware (material, part and product) flow and the broken lines show information flow.
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1. The customer order enters the information system and is immediately available to the entire manufacturing chain, although the final assembly is where the order is retrieved and the manufacturing is initiated. Any sales department involved should have their work immediately registered to avoid increased lead-times. AIP does not specify the customer to be end customer. The company shown in figure 3.3 may be a sub-contractor to other companies.

2. The final assembly will be able to see which orders are in the system at an earlier stage. This will lead to a more responsive production.

3. One of the central concepts about AIP is the modularisation of products. The modules and standard components will be stored close to the assembly. When an order is to be executed, components and modules will be taken from the storage and assembled into products. The levels in the storage will be high until the AIP introduction phase is over, but would be lowered over time. The goal is to eliminate the module storage.

4. The finished products are, after the assembly, packed and delivered to the customer.

5. The module storage is set just before the module (assembly) workshops. Modules are produced to keep the levels in the module storage at a preset value. To avoid delays, the module workshops will have to be able to deliver the modules required by the assembly workshops at the correct rate.

6. The demands placed upon manufacturing and ordering of components are basically the same as the ones placed upon modular workshops, to deliver quality components and material on time.

One should note that the sub-contractors could deliver to any station in the chain. That is; they could deliver raw material or components of different levels of completion, from simple components to product modules as well as material not directly included in the final product, like packaging material.

What AIP introduces is the possibility to give a product its final identity late within the production chain. This is of great value in a world in which the variant flora is commonly created in parts manufacturing, with ensuing buffers and warehousing problems. It becomes obvious, then, that the application of the AIP strategy requires a highly reactive, order-driven control system and equally efficient assembly workshops.
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As stated in section 3.1, the basic AIP design takes into account:

- Reconfigurable manufacturing systems.
- Product design that assist the production processes and at the same time being attractive to customers.
- Reconfigurable and responsive information systems that are designed to support the processes.
- A supply chain that supports the manufacturing processes and that strengthen the production as a whole.
- Competent and flexible personnel.
- Other personal related subjects like human-machine interfaces, working environmental issues etc.

AIP is designed around the goals and the coupled technical requirements. The coupled technical solutions form the basic structure and goals to work towards and are to be considered needed in the long run. They could be introduced step by step over a period of time. The technical requirements are developed from recent applied research and technical or organisational solutions that are available, either as commercial products or at a prototype stage or research stage; however some additional technical development may remain to be done. The technical requirements for AIP are:

**Standardised production equipment:** To be able to quickly reconfigure the system, it has to have some sort of standardisation built in. The AIP description assumes that the system is reconfigurable to some degree.

**Modular product design:** One building block of AIP is the modular product concept and the Modular Function Deployment method (Erixon, 1998). Therefore, the products are to be of modular design. The product modules should be possible to combine to create many different end product variants from a lower number of variants of product modules.

**Standardised components:** This applies to products as well as production equipment. It helps to augment the benefits with a modular design. The components that cannot be built in a module are supposed to be standardised.

**Instantly available information:** Product data, current capacity levels, inventory levels, current order levels etc have to be available to make the right decisions. The AIP is designed around the availability of accurate such information.
Tailored production planning and control: The different parts of the manufacturing within an AIP system are to be optimised when it comes to production planning and control (PPC). Therefore different PPC systems are to be used on different parts of the production.

The AIP strategy is based on the fact that the traditional line-type assembly will only be applicable in some forms of final assembly. The predominant solution to be preferred, as long as the product features allow it, is the dedicated assembly workshop, possibly in cell form. Basically, an efficient final assembly requires an equally efficient set of sub-assembly or module-assembly units. That is to say that, if AIP is to become successful, equally reactive and truly flexible assembly solutions must be developed. Due to this conclusion, the AIP project has been conducted in parallel to the Hyper Flexible Automatic Assembly (HFAA) project (Onori et al, 1999). This project will develop modular, process-oriented assembly system components. The objective is to produce a hyper flexible assembly solution that allows the user to go from simple manual assembly to full-scale automatic assembly in an economically and strategically stepwise manner (Onori et al, 1999).

3.2.3 When to use the AIP strategy

The AIP strategy means a manufacturing arrangement and a product design strategy that transforms the customer order situation of high variability when it comes to variants and numbers, to a repetitive and continuous flow situation for the manufacturing.

What AIP introduces is the possibility to give a product its final identity late within the production chain. This is of great value in a world in which the variant flora is commonly created in parts manufacturing, with ensuing buffers and warehousing problems. It becomes obvious, then, that the application of AIP strategies requires a highly reactive, order-driven control system and equally efficient assembly workshops (Onori & Karlsson, 2000).
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The basic design of AIP is to support both large companies as well as Small to Medium Sized enterprises (SME). The problems for SMEs associated with outsourcing, within the new global economy, may be summed up as:

- The JIT parameters are even tighter (Wilson, 1997).
- Modular product design demands are increasing (Erixon, 1998).
- Competence levels need to be increased.
- Volumes increase and quality levels have to be even.
- The number of customer-specific variants is increasing dramatically (Warnecke, 1993).

Another possible problem, especially for smaller companies is the cost for equipment, personnel and the implementation, making a statement on the possible gains by using AIP somewhat hard to foresee. One could however argue that by applying AIP, SMEs would be able to supply the major companies with products that vary in demand, at the right time, in as many customer-specific variants as required, and at constantly high quality levels.

Whether manufacturing as specified within the AIP strategy is desirable or not, depends as just indicated, on many different factors.

First, it is assumed that there is a need for a highly developed customer oriented production. There should be a demand for customer specific products to be delivered in a short time. One could argue for the development of a trend in the international market, which goes in that direction, but that has not been the case always, and it is not certain that it will be so in the future. Predicting the future trends of manufacturing regarding these aspects is outside the scope of this thesis and therefore left without further research and evaluation.

3.3 AIP-related production system requirements

The goal with this section is to present ideas usable in an AIP environment as specified earlier in this chapter. Some highly interesting technical solutions have been looked into. Different production related areas are covered.
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The research has been conducted as discussions and interviews with key personnel, surveys and case studies at 19 companies, over a period of approximately three years. Of these companies, 10 have been subject to surveys and case studies on location and the rest have provided persons for interviews and discussions. The results from the studies have been directly linked to similar problems and related solutions found in literature.

Supervisors at one of these companies have demanded for their company to be totally anonymous and its name cannot be used. People from some of the other companies have stated that no exact numbers are to be printed and that specific information cannot be directly linked to their company name. Therefore, company names have been excluded entirely.

3.3.1 Introducing the research areas

Production has been divided into five areas. The borders between the areas are not defined exactly since they are used to point out the importance of including many different production related factors in strategy design and use.

The defined areas are:

**Materials supply**: This area covers the issues of transportation to and from a manufacturing unit. The internal transportations are not covered here. Many of the issues, normally associated with logistics, are placed within this area.

**Human resources in manufacturing**: Included here are issues as workplace design both for improving operations effectiveness and the health situation of the workers. Organisational issues are placed within this area as well. This area is not widely covered in this thesis.

**Manufacturing processes**: This area is to cover machine related issues of all sorts. Examples of such issues are reduction of resetting-times, development of machine cells, flexibility of manufacturing systems, automation etc. Assembly processes are included here as well as packaging and such operations.

**Product design**: Designing and developing products to support the AIP strategy. Most notable here is product modularisation and standardisation of parts. This is a very important area since AIP is being designed around modularised products.
Information handling and use: Aspects regarding getting the right information to the right place at the right time is placed here. This includes researching which information to distribute as well as hardware and software solutions for information distribution. Production Planning and Control (PPC) and Product Data Management (PDM) are examples of research areas of immediate interest. Ordering between processes is included in PPC.

These areas are many times closely related and changes made in one area affect the others in different ways. This is very important to remember.

The reason for covering all areas is that AIP is to be a strategy that looks upon production as a whole and considers the possible gains to be made by coordinating efforts. The inherent design goals of AIP, presented in chapter 1, also require a simultaneous development of all areas. The common goal with the solutions and ideas presented in this chapter is to accomplish AIP and the advantages that come with it.

No suggestion on which area is most important is made in this thesis. The amount of text covering each area respectively is therefore not reflecting any degree of importance of the area. Each topic is a research area of its own and the idea with this chapter is to give an insight in each topic in order to clarify the constraints posed by AIP on each of them.

3.3.2 Materials supply

Early on it was found that the AIP strategy fits very much into Supply Chain Management (SCM). A supply chain is viewed as a set of order-linked and sequentially interdependent actors passing material objects (products) in a uniform direction. This is done from the stages of raw materials, along several steps of manufacturing and assembling through various stages of moving, storing and selling to the final customer in order to satisfy customer demands. Areas to be optimised include choice, service, speed and cost (Otto & Kotzab, 1999). Consequently, SCM is about managing such a system.

Balsmeier & Voisin (1996) classifies SCM as formal linkage among all levels in a marketing channel; it is a technique that looks at all the links in the chain from raw material suppliers through various levels of manufacturing and distribution, to the final customer. SCM may be seen as an overall strategy for all parts in a supply chain, including manufacturing and assembly. This becomes clearer when looking at Otto & Kotzabs (1999) attempt to condense SCM principles.
- **Compress**: Improving a supply chain by (1) reducing the number of nodes, members or actors in the chain, (2) or by reducing the physical distance between any two nodes. Compression primarily applies to structure and aims at costs.

- **Speed up**: Improving the supply chain by reducing the amount of time necessary to move between any two nodes in a chain or a network or between two stages in a process. Speed up primarily applies to processes and aims at time.

- **Collaborate, cooperate**: Improving a supply chain by increasing the intensity and scope of cooperative behaviour between two or more independent decision making units. Collaboration primarily applies to relationships, planning, scheduling and execution. It aims at cost and service.

- **Integrate**: Improving a supply chain by reducing the penalty in time, effort, cost or performance to move between any two activities in a process or between processes. Integration primarily applies to processes and aims at time and cost.

- **Optimise**: Improving a supply chain by maximising the value of a target function through the use of quantitative models and methods. Optimisation primarily applies to planning and scheduling and aims at time and cost.

- **Differentiate, customise**: Improving a supply chain by increasing the specificity and thus the effectiveness of a subject towards a given purpose. Differentiation primarily applies to structure, processes and planning and aims at cost and service.

- **Modularise**: Improving a supply chain by reducing the penalty in time, effort, cost or performance to replace a particular segment of the chain. Modularisation primarily applies to products and processes and aims at cost and time.

- **Level**: Improving a supply chain by reducing the magnitude of variation of a certain parameter of an object over time. Levelling may apply to material flows and order flows. Levelling primarily applies to goods and order flows and aims at cost.

- **Postpone**: Improving a supply chain by moving the product differentiation closer to the time and locus of consumption.

Mapping these SCM principles to the AIP strategy description shows many similarities. Some of the principles are identical to AIP ideas. *Postpone* is similar to the AIP idea to create product variants as late as possible in the
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production, which is in the final assembly. Modularise is one of the ways to accomplish this. Modularisation is a central part, both in product design and in manufacturing equipment. Compress, speed up, collaborate and integrate are directly suggested as ways to accomplish AIP. Optimise has so far not been addressed within AIP. The reason being that no specific issues has yet been finally classified within AIP, but optimisation will most likely become an issue when implementing the strategy. One has to remember that optimisation of, for example inventory levels of lower value material and components are sub-ordinated delivery time and accuracy of delivery to customer. Level issues are handled by accomplishing flexibility within the product design, the information system and the production system and not by trying to level the variations. This is a difference between SCM and AIP.

One problem found in supply chains is the so-called bullwhip effect. The bullwhip effect is the amplification of order variability along the supply chain. The closer to the first link in the chain, the larger the variability. This is also known as the whiplash effect. According to Lee and Padmanabhan (1997), bullwhip effects is caused by

- Demand forecast updating: This occurs when each stage in a chain does its own planning, based on the demand given by the stage before. Each stage will build up a safety storage based on that stated demand as well. This causes a larger inventory than necessary and a bullwhip effect.

- Order batching: Periodic large increases in demand caused by low frequency sampling of customer demand as well as other, non production related events.

- Price fluctuations: Increased customer demand due to shiftings in prices. The shiftings has many causes like special prices and discounts.

- Rationing and shortage gaming: Unexpected customer behaviour like over-ordering from different suppliers and then cancelling the other orders when the first delivery takes place and such. Also gaming for end customer demand by the seller and then returning the over-ordered non sold products to the manufacturer.

The effective way to eliminate bullwhip effect is by allowing viable information available and to create short delivery-times. Both are built in features in the AIP strategy and therefore bullwhip effect should be of little or no concern.

In the surveys and following case studies, materials shortage was during the interviews said to be one of the most important factors causing delays in the
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manufacturing. In half of the cases, it was said to be the most important factor. This applies to bought material and components as well as components made in house. Material shortages did from time to time, cause situations where the manufacturing schedule had to be re-planned. There were also situations when the schedule was ignored and supervisors planned the manufacturing, setting aside the plan presented by the scheduling system. The importance of accurate deliveries and manufacturing plans could therefore be said to be high.

Some of the companies had to deal with large amounts of stored material and components of different specifications. Therefore a large amount of article numbers had to be administrated. This made it harder for material managers to keep track on the correct inventory figures. Admittedly, significant percentages of the stored inventories were components or material that was cheap to acquire, making it possible to use simpler methods for inventory control and to overstock. It was, however an outspoken wish from material supervisors to lessen the amount of unique articles in storage. Material supervisors considered it to be an area with large potentials for improvement.

One of the visited companies is manufacturing and buying components based on levels in a central, in-house material storage facility. The products are assembled to order and the components are picked from the material store. When specific levels are reached, the store is filled up to a pre-selected level. In this specific company, they have an accurate file on inventory levels. The main reasons was said to be the simple ordering methods used and the good relation with vendors, resulting in material related information to be available where it is needed, when it is needed.

As indicated above, on all the studied companies, there are links between the handling of inventory related information and the material handling itself. For example, in order to have a good overview of the inventory situation, it is also found to be important to update the inventory levels in the planning and control system frequently. This was especially illustrated at one of the studied companies, where they received material and components each weekday but updated the inventory files only once a week. This caused some problems with delays due to material shortages. It also caused problems with inaccurate inventory levels since workers stockpiled certain important components since it was a risk to run out of them otherwise. When checking up on the inventory levels, the inventories stored at the workstations was never or rarely discovered and therefore not included in the inventory file.
External transportation was not included in the surveys and case studies if workers or supervisors did not explicitly present it as a source of problems. This happened in two cases, concerning delivery between sub-contractors and the studied company sometimes being late. A common solution, mentioned also by supervisors when being interviewed, for creating an effective external transportation system is to use third-party logistics. Although slightly different, outsourcing logistical functions is an increasingly popular phenomenon in Europe as well in the United States (Allnoch, 1998). Using an outside company for transportation may give lower transportation costs, higher delivery frequencies and better service due to the effects of large-scale activity.

Third party logistics companies do not merely supply transport. They offer knowledge of vital information like customs laws and import duties and provide services such as order tracking and other transportation related information. The manufacturing companies are to some extent, replacing inventory with information (Woolley, 1997).

On the other hand, there are also companies that treat the transportation as a strategic activity and therefore keep it in-house. The possibly higher direct transportation costs are then of lesser concern.

Whatever path may be chosen, there is a need for highly optimised transportation management practices at the strategic, tactical and operational control levels. Lack of planning and co-ordination is the cause of excess travel for commercial vehicles, with detrimental effects on economy and environment (Hasle, 1999).

AIP does not specify how to arrange transportation. It however puts some demands on it:

- Frequent enough to keep inventory down and the delivery-times to customer short.
- Consistent enough for not causing production stops due to lack of material or components.
- Consistent enough for not causing quality problems. Transportation cannot be allowed to affect the material, components or products. If the transportation has such influences, it may cause delays due to quality problems.

AIP does not specify how supply activities should be conducted; however it places some demands on it as described in this chapter. The possibilities by using SCM as an overall strategy within AIP ought to be great, looking at the similarities. SCM also points out the importance of an overview of the
production to be able to make anything from noticeable to large improvements.

3.3.3 Human resources in manufacturing

Although being a very important area, an in-depth look at this research area has been left outside the scope of the thesis. This means that there are no solutions suggested here, but important issues are identified and discussed. It was clear in the pre-studies that the areas concerning human resources have a considerable impact on the performance of the production. It is therefore a research area to put efforts into.

Early on in the studies, different personnel-related issues were identified. These are divided into the following areas:

- Organisational issues: The dividing into work groups, formal and informal channels for information distribution, authority etc.

- Competence issues: Education, knowledge about operation and the products, choosing an education and knowledge level on the employees.

- Work environmental issues: The creation of a workplace that is stimulating to work within, forming a workplace layout that promotes effective manufacturing, working to reduce and avoid work related injuries etc.

The areas interact in different ways, which is also to be considered.

AIP presents some special demands on human resources issues that have to be solved. Basically these are dependent on the demands placed on the production as a whole. They are the demands for flexibility, speed and robustness. Since the machinery and information systems are to be changeable to fit the current order situation, the personnel have to be able to do so as well. This could, for example, be done by seeing to it that the operators have the knowledge about many different processes and therefore will be able to work where needed. This approach is suggested for cell manufacturing where such situations may occur, by among others Estrada et al (2000).

There are also examples in the studies of cell manufacturing where independent work groups with personnel having a wide knowledge about many processes, and therefore being able to handle any task done within the cell (Karlsson, 2000a). Such cells can work independently from outer detailed control, since many problems can be handled within the cell. This is a
feature sought after in an AIP system. A wide knowledge base among the personnel also contributes to the overall flexibility of the production.

To be able to get the desired educational level, the company either has to be able to hire educated and experienced persons or educate the employees themselves. Both are resource demanding. Sometimes the desired competence is unavailable. Henry Ford has dealt with such a situation (Camarrano, 1997) and it is also the reality for companies today. The solution Ford used was to make the tasks simple so that an unskilled worker could handle them with a minimum of education. This makes it possible to temporarily employ personnel to cope with, for example, shifting production volumes. With the repetitive work tasks came the repetitive straining of the same body parts over a long period of time. Stressing the same body organs will over time, build up more or less serious injuries (Ericson & Odenrick, 1994). Therefore such a solution is less relevant for AIP.

Important when creating a good working environment is the workplace design. There are many ways to design a workplace to reduce the effects of repetitive work tasks, but these should be built in even if there is a rotation between tasks among the operators. Then the capacity lost due to sick-time will be reduced and the work environment will be more attractive. This will also make it easier to employ staff, since the company can provide interesting work and show that they care about their employees (Allwood & Thylefors, 1994).

Making the work place a safer and less straining place to be at, may be done in many different ways. By using colour markings, using the appropriate lighting, reducing sound levels, use adequate room heating (or cooling), using ergonomic equipment etc, are in line of improving the work place (Akselsson et al, 1994).

Making the work place safer is also quite similar to making the work place more effective in a production point of view. Time lost due to looking for misplaced toolings, fixtures and materials is a common situation. The correct working instructions have to be instantly available as well as the current situation, when it comes to machine status, available personnel, material etc. The operator has to know where to retrieve this information. A lot can be done when designing work places. Specifying placements for different tools etc, is a possibility that has been proven effective in use within, for example Toyota. Then tools are not misplaced and the time, earlier used for finding the right equipment, could be used for manufacturing.
The simplicity called for in tool placement and such, was also found to be valid for human – process interfaces. If the interface was not easily used and found to aid the user in his or her work, it was likely that the task or problem was to be solved in another way, bypassing the process if possible. Information distribution and manufacturing control are two examples of processes that could be bypassed. Component storage at the workplace in order to never to run out of components is another example. If the systems aimed at aiding in those processes were easy to use, they would be used more often.

The way that the workforce used the process interface showed some more interesting results. If the interface provided a two-way communication in which the operator would have good use for the information made available by the interface, it was more likely that the user would provide the process with accurate information as well. If the operator does not consider communicating with the process through an interface a burden, the operator most often would see to it that the interface remains a useful aid in his or hers work.

Observations made at the studied companies supports the idea that workers and supervisors alike contribute highly to the overall flexibility and capacity of a manufacturing system. The linkage between the processes themselves and the workforce helps to maintain that flexibility and capacity.

### 3.3.4 Manufacturing processes

**Definition of process**

The process is here defined to include both strategical as well as machine related issues. The definition is loosely modelled after Rampersad (1993). Notable when discussing a process definition are the factors of:

- The choice of methods on a higher level of abstraction.
- The structural choice of sequences and relationships between single operations.
- The operations. The division of work tasks into single operations.
- The system layout, the arrangement of the physical system, the location of and relationship between apparatus etc.
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- The system structure; involves a set of system components
- The system components which fulfil functions within the system

The first three points cover the strategic, theoretical work with the system and the last three are about the system, including actual components and machinery.

Rampersad (1993) only includes the first three points in his definition of the process. The last three, he defines as system. However, these last three points are often included when discussing processes in literature. All six points also describe areas which are to be worked with according to the AIP structure. A relationship between the product and the process is also noted.

The existence of product development methods that aim to simplifying manufacturing of the product provides examples of how this relationship is constituted. Examples of such methods are Design For Manufacturing (DFM), Design For Assembly (DFA) and Design For Automatic Assembly (DFA2). The coupling between the product design, the process (here the assembly process) and the system design is illustrated by Rampersad (1993).

Figure 3.4: The relationship between the system, the process and the product (Rampersad, 1993).
The thick arrows designate a stronger relationship than the thin arrows. The interactions between the variables at the same level of abstraction are the strongest. Rampersad (1993) only covers the assembly process, but this relationship and definition is used in this thesis, in a wider perspective to cover other production system areas as well, not only assembly.

**Flexibility issues**

As argued for earlier, the design of the process and the design of the product are closely related and depend on each other. The degree of dependence of course, differs from case to case. This was observed frequently during the studies. Product related factors affecting flexibility could be dimensional, weight, environmental etc, which decides the possibility of manufacturing the product.

The AIP structure aims at lessening the dependence, or at least the effects from it. If one systematically works with increasing the flexibility of the processes as well as with making the product designs easier to produce, a situation occurs with simultaneous manufacturing flexibility enhancing work. This means building processes that are able to adapt to the manufacturing of products, matching the current order situation. It would result in a system with a larger total flexibility, which therefore is a basic principle of the AIP system design.

In order to accomplish a high level of flexibility, many of the studied companies used a department layout for their manufacturing. Those companies had to manufacture many different products and product variants. The worst case being a company that sometimes has to manufacture spare parts for vehicles made as early as in 1960 and onwards, meaning that for each year, the number of different variants of manufactured products increases significantly. This could make it hard to modularise or standardise parts and moving towards an AIP approach. A conclusion made during the studies is that it would necessarily not be easy to accomplish AIP in a short period of time.

**AIP and automation**

A conclusion from the studies is that one has to get capability in the form of flexibility out of the production equipment. Some may be able to do that by
using their ordinary machinery, depending on machinery available and the product manufactured. In the companies studied within the pre-studies, it was observed that using manual operations was bringing about a great deal of the necessary flexibility in assembly operations. This is rather common in the industry and especially when it comes to assembly. AIP does not specify the use of manual or automatic processes. There are however situations where assembly automation is preferred (Tichem, 2000):

- Cost reduction. Labor cost amount to an important part of the total production cost.
- High and constant quality. In a human centered assembly process, errors occur. Parts may be assembled in a wrong way or not fully connected. Sometimes not even assembled at all. Automated assembly contributes with a high and consistent quality.
- Technical necessity. There are no other possibilities to assemble the product. This could be due to miniaturised products.
- Shortage of assembly workers. There are predictions of a shortage of labour forces in the future. This can be noted in some industries already.
- Bad working conditions. Many jobs are dirty and/or dangerous. Automation can reduce amount of such jobs.

There are however, some problems associated with implementing and using flexible automated assembly systems. They are (Tichem, 2000):

- Wrong attitude and strategy towards assembly and assembly automation. Mainly introducing proper education solved this.
- Insufficient production volumes. This problem is addressed by designing product families with common parts, designed for automatic assembly and developing and applying standard assembly processes.
- Uncertainties in predictions on production volumes and family characteristics. Designing product families with common parts, developing expandable system concepts and develop standard assembly processes are possibilities here.
- Products are not designed for assembly. Educate and implement DFA methods. Develop DFA tools.
- Unreliable techniques. Develop reliable techniques and avoid specific solutions. Standardisation of assembly processes.
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- Lack of planning, programming and control aids. Develop such tools, reduce planning, programming etc by standardisation on system level and operations and equipment level.

- Badly conducted introduction of flexible automatic assembly projects. Use proper set-up of automation projects.

These are apparent factors to consider when developing AIP processes.

A suitable solution to flexibility problems in automatic assembly would be the Hyper Flexible Automatic Assembly project (HFAA)(Onori & Alsterman, 2000). HFAA describes a concept consisting of a set of equipment modules, with standardised interfaces. The benefits to be gained from a standardised solution are many, among others:

- Shorter installation times.

- Lower investment costs and related risk factors.

- Simpler re-configurations of original layout.

- Second hand market equipment.

These benefits are in line with the features wanted in an AIP processes. One problem is the fact that the assembly process itself has never truly been structured and standardised (Onori et al, 1999). This makes it harder to create a set of standardised assembly-oriented equipment (Onori & Alsterman, 2000). AIP does not put any additional demands on the assembly equipment that are not addressed in the HFAA project. They are on the contrary, quite similar.

Structuring a manufacturing flow

A possibility when it comes to arranging manufacturing is to create cells. Traditionally the design of production systems has been done in an operation-based manner with individual subsystems being optimised independently of overall system objectives. Equipment used within cell manufacturing must incorporate suitable design parameters to meet the functional requirements from cell manufacturing. Customised equipment design enables cellular fabrication to be possible and highlights the importance of equipment design that achieve the system-level objectives (Shukla et al, 2000). The equipment design parameters within the HFAA project supports the ideas of re-arrangeable cells and therefore the arrangement of AIP.
When it comes to parts manufacturing, the demands are almost the same but with some exceptions. Automatic assembly equipment including feeders and other additional equipment is still costly. Some automated manufacturing equipment is not as costly or even cheaper, compared to its assembly counterpart. If the machinery is relatively cheap, the problem could be solved by having an over capacity in those areas. Otherwise one should aim for reconfigurability by using standardised interfaces in this area as well. Parts manufacturing is very important since short and accurate delivery times is impossible if there are no components available. The quality of the manufactured parts also contributes to the overall quality of the product.

It is often stated that a line type of layout is more sensitive to disturbances than a department type of layout. This does not mean that a department layout factory is insensitive to disturbances. It was observed during the studies at several times, that there were one or more manufacturing processes that often caused disturbances. Asking certain people about it gave the information that those disturbances only caused local problems for the operators to fix and that it did not affect the rest of the manufacturing. Following the manufacturing flow and also asking the personnel at the last station, often packaging and shipping, about it, the results were often different. The disturbances were hidden in the lead-times available in the MRP system, which were a lot longer than necessary. Most often the products left the plant on time, but the variations in arrival time to the last process, varied most considerably. The cause for the delays was not always due to the known single or few disturbance prone processes, but the problems could surprisingly often be derived to those processes. The disturbance effects through the plant often behaved like the bullwhip effect, causing larger fluctuations along the flow.

Therefore, the conclusion has to be that department layout factories are not insensitive to disturbances, but the disturbances could easily be hidden in such an environment, characterised by lack of control.
A similar effect could be seen at different processes, which are sensitive to disturbances themselves where small variations in input could result in different disturbances in the output. These disturbances were found to be of different kinds.

Either the shifting input volumes caused disturbances resulting in different workloads for the process, forcing it to increase its capacity. Or there could be disturbances forcing the process to wait for material or resources to be able to continue the manufacturing operations.

This type of disturbances makes the accomplishment of a steady flow of material and resources a high priority, but it also should induce research and development of non-sensitive processes in general for use in an AIP environment.
3.3.5 Product design

Products designed to consist of standardised modules and other components is a cornerstone in the AIP strategy, since AIP is designed around it.

Design for X

Figure 3.9: DFX versions mapped according to relationship with each other (Eskilander, 2001).

With the AIP requirements, presented earlier in mind, it is likely that existing DFX methods will be useful within AIP. Examples of such methods are shown in figure 3.9. This means that there are no immediate needs to develop DFX methods for AIP. The ones available cover the demands put on the product by AIP. Mainly the DFXs to use are DFA with the sub-groups DFAA and DFA for manual assembly. Potential benefits for using DFA are according to Egan (1997) divided into short-term and long-term improvement categories:

Short-term, initial goals for implementing DFA are often cost based, typically:
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- Reduce number of components
- Reduce assembly time.
- Reduce manufacturing and assembly costs.

Long-term, that is when applying DFA on more than one product there are potential long-term goals or effects for the company:

- Improved product quality
- An environment for concurrent engineering.

Both the short-term and the long-term improvements are benefits that are needed within AIP. Therefore DFA is a natural set of methods to use here. This is also valid for the related methods DFA2 (Eskilander, 2001) and DFA focused on manual assembly. Since the product design is different in an AIP system, than it may be ordinarily, there is a need to look at the DFA-methods available to see if they fit. The results from using them should be a product suitable for the specific type of production.

Demands for using other DFX-versions, Design For Manufacturing (DFM) are put on the product by the environment and not by the AIP strategy itself. This does not mean that they could be disregarded, only that they very likely are unaffected by AIP. DFM for example, is a very important field of methods, since the lead-times up to the final assembly are to be as close to zero as possible. This makes the manufacturing of parts extremely important to work with but there are no special demands placed upon the DFM methods that are not valid in other, non-AIP situations.

Onori & Alsterman (2000) address the lack of a structured definition of the assembly process as a problem when using DFA. The DFA methods are basically formed after human requirements on the product and therefore do not render it easy to assemble automatically. A solution to this problem could be the DFA2 method (Eskilander 2001). Therefore the DFA2 method is likely to be a part of an AIP implementation method.

Modules and modular issues

Modularisation is the decomposition of a product into building blocks (modules) with specified interfaces, driven by company specific reasons (Erixon, 1998). One way of creating modular products is by using the Modular Function Deployment (MFD) method, also described in Erixon (1998). The central part of MFD is the Module Indication Matrix (MIM). In
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this matrix, technical solutions are characterised by strategic reasons for why a technical solution should be a part of a specific module. These reasons are called module drivers (Stake, 2001a). The module drivers represent important factors regarding the life cycle of the product:

- Carry-over: The module is to be used in other, future products.
- Technology push: The module is likely to be a subject to technical advancement during the product lifetime.
- Planned design changes: The module will be subject to design changes during the product lifetime.
- Different specification: The possibility to use different modules and thereby creating end products with different specifications. This is a way to create a product family.
- Styling: Modular design allows the creation of differently styled product variants. Modules are then constructed differently concerning color and shape. This is also a way of creating a product family.
- Common unit: A module that is used in many products across a product family.
- Process/organisation: The module suits a special process or has a suitable work content for a group.
- Separate testing: Allowing a module to be tested separately.
- Strategic supplier: A module may be outsourced.
- Service/maintenance: A module may have to be easily removable for service and maintenance.
- Upgrading: The module may be shifted for upgrading a product to one with better performance.
- Recycling: Parts that are to be recycled after the end of the product life may be within modules for easier recycling.

One idea with using modularised product design is to be able to create many product variants by assembling a few different variants of product modules. The nature of the product part structure is partly determined by the number of parts used at each level of production (Stake, 2001a). The part structure will form the environment in which the manufacturing is to be conducted in the case of how many variants must be handled at different stages of the production. Slack et al (2001) describe four different shapes of product structures.
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Figure 3.10: Different shapes of product structures (Slack et al, 2001).

The A-shaped describes a wide range of part variants resulting in a few number of end product variants. T-shape describes a large amount of customised product variants, manufactured from a low number of part variants in relatively standardised processes. V-shape describes a situation similar to the T-shape but with the difference that the V-shape has less standardised processes. Finally, the X-shape describes a situation with modular products where a small number of module variants are assembled into a large amount of end product variants. The modules are however manufactured from a wider range of part variants.

Looking at the AIP production strategy, and mapping it in a similar way as Slack et al (2001), gives:

Figure 3.11: A representation of an AIP system according to the product structures in figure 3.10. AIP is an x-shaped product structure, here being depicted tilted 90 degrees to the right.
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The amount of reduction and increase respectively, in each stage is somewhat dependent on many factors, including the product design. Therefore the picture is not to be seen as an exact illustration of such issues. It is merely an illustration of the aims of the AIP strategy.

Analysing the module drivers, the primary drivers for AIP are different specification, styling and common unit, since they are central building blocks of the AIP strategy. They make it possible to create product variants within the final assembly. Secondly, to improve overall flexibility of the production, the drivers carry-over, planned design changes, technology push and strategic supplier are important. The remaining drivers, although important, are not necessary for AIP. Some of them could however, be important for the customers. The driver process/organisation is not valid within AIP since the production system should be flexible enough to counter such needs.

Standardisation of parts

A key issue in AIP is the standardisation of parts. This includes everything from the simplest duct tape to the product modules. There is an increasing cost related to an increasing number of different component variants, but that is not the most important here. If the parts are not standardised and widely used within the production, the idea of making many product variants from a low number of part variants, will most likely be frustrated.

Some of the studied companies could present cases where they had managed to standardise component, especially simpler components as screws, product covers, cables etc. All companies that had attempted such a standardisation had succeeded. Standardising more complex parts or modularisation projects had only been attempted by a few of the companies but with limited success. The main reason for not succeeding entirely was, according to the interviewed supervisors, that a standardisation and modularisation project needed more resources that the companies had committed to that particular project.

Final words on product design and AIP

A conclusion is that focusing product design goals towards the intended manufacturing goals is of outmost importance for AIP. This design strategy
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should be both short-term and long-term, taking into account modularisation and standardisation of parts as well as making the parts easy to manufacture and the product and sub-assemblies, easy to assemble.

3.3.6 Information handling and use

Information distribution and handling is a large and important area within production. Mentioned here especially are Product Data Management (PDM) and Production Planning and Control (PPC). The availability of product data was identified as important in the study interviews and is therefore covered. PPC was also identified as being important, both at the plant studies and in the interviews.

**Product Data Management**

PDM is a comprehensive tool for the administration of the product data that is used within the product development process. Information about for example, specifications, CAD-models, FEM-models, NC-programs and project plans is available. The data is created in other computer programs and systems, but administrated within the PDM system. The purpose is to manage documentation concerning the entire life cycle of a product. PDM systems may be used for classification, life-cycle analysis, file handling and management, reviewing etc.

The challenge is to maximise the time-to-market benefits of concurrent engineering while maintaining control of your data and distributing it automatically to the people who need it, when they need it.

The way PDM-systems cope with this challenge is that master data is held as a unique copy in a secure vault where its integrity can be assured and all changes to it monitored, controlled and recorded. Duplicate reference copies of the master data, on the other hand, can be distributed freely, to users in various departments for design, analysis and approval. The new data is then re-registered back into the vault. When a change is made to data, what actually happens is that a modified copy of the data, signed and dated, is
stored in the vault alongside the old data, which remains in its original form as permanent record. This is the simple principle behind more advanced PDM systems (Williams, 2001).

PDM systems originate from engineering aspects of product development, so the systems mainly deal with product engineering related data. PDM systems rarely use and treat data like for example, sales, costs, supply-issues or manufacturing control. Some of the basic functions of a PDM system are (Peltonen, 2000):

- Mechanism for associating objects with attributes. The properties of documents and other objects are described by means of attributes, which provide information about an object. The attributes could also be used for finding objects.

- Management of temporal evolution of an object through sequential revisions. The evolution of plans and other design related objects is usually captured in the form of successive revisions. This is an important function since a lot of design work usually consists of modifying existing designs.

- Management of alternative variants of an object.

- Management of the inspection and release procedures associated with the objects. Changes to objects must be approved before they are released for general use.

- Management of recursive division of an object into smaller parts.

- Management of changes that affect multiple related objects.

- Management of multiple views of an object. A product could be divided into components in more than one way.

- Management of multiple document representations. For example, a CAD model could be available in a native CAD format and in a neutral format for viewing.

As one can see, the functions are dependent on one another. Another observation to make is that PDM is very much about managing configurations and changing of configurations.

According to the PDM Information Company (2001), there are 9 benefits with implementing and using a PDM system:

- Reduced Time-to-Market: It can speed up tasks by making data instantly available as it is needed as well as supporting concurrent task management. It also makes it possible to access all relevant data, all the time, with the
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assurance that it is always the latest version.

- Improved Design Productivity: A design engineer would spend as much as 25-30% of his time handling information. The identification, re-use and modification of existing similar designs should become routine.

- Improved Design and Manufacturing Accuracy: Everyone involved in a project is operating on the same set of data, which is always up to date.

- Better use of Creative Team Skills: The risks of spending excessive time on a new design approach, which may not work would be undesirable. Use of PDM may reduce the risk of failure by sharing the risk with others and by making the data available to the right people fast. It also helps to keep track of all the documents and test results relating to a given product change, minimising design rework and mistakes.

- Comfortable to Use: In a conventional working environment, users would either have to be much more skilled at accessing the information or be prepared to accept it in a much less flexible form. The system should, in fact, make familiar tasks much more user-oriented than before.

- Data Integrity Safeguarded: The single central vault concept ensures that, while data is immediately accessible to those who need it, all master documents and records of historical change remain absolutely accurate and secure.

- Better Control of Projects: Because the immense volume of data generated by the project rapidly snowballs beyond the scope of traditional project management techniques.

- Better Management of Engineering Change: A PDM system must allow you to create and maintain multiple revisions and versions of any design in the database. This means that iterations on a design can be created without the worry that previous versions will be lost or accidentally erased.

- A Major Step Toward Total Quality Management: Many of the fundamental principles of TQM, such as empowerment of the individual to identify and solve problems are inherent in the PDM structure. The formal controls, checks, change management processes and defined responsibilities should also ensure that the PDM system you select contributes to your conformance with international quality standards.

PDM is very much a set of tools to incorporate in the further development of AIP. The expected benefits are well in line with the goals of AIP. However, it should be developed as an integrated set of tools, supporting AIP ideas and
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goals, not as a separate system that grows into enormously large software solutions that will be too expensive to install, set up and use for small to medium sized companies.

**Production Planning and Control**

The question as how to design the Production Planning and Control (PPC) for AIP production arouse early in the study phase, considering all the problems related to PPC noticed. Among the problems that have been identified are:

- Little or no control over the actual situation.
- Lead times, given by the PPC system, were often inaccurate.
- PPC systems are not designed for the given type of production or the way the companies produce.
- Unfriendly user interface of PPC software.
- The real material flow does not comply with the model in the system.
- Poor or non-existing handling of rush orders.
- The system is often considered a burden rather than a helpful tool.

A problem found at smaller companies in the studies, was the cost of an ERP type of software system. The systems available was said to be too expensive for them to buy. These problems have to be solved and, as the work proceeds, more problems will most likely appear. To be able to decide what system or principle to use, a review of the benefits and limitations of each system was necessary.

Materials Requirement Planning (MRP) is flexible in terms of products and floor layout, but contributes to long lead times and large inventory levels. JIT, on the other hand, has a narrow range of product and layout flexibility, but builds up minimal inventory levels and gives a short lead-time (Plenert, 1999a). At the same time, there are many other principles to be considered, e.g.- Bottleneck Allocation Methodology (BAM) (Plenert, 1999b) and Theory Of Constraints (TOC) (Goldratt and Cox, 1986; Goldratt and Fox, 1986).

AIP sets demands on short lead times and low inventory, but at the same time the PPC system has to be flexible to cope with the changes in layout and product mix that AIP is designed to handle. Low inventory levels and
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short lead-times usually lead one to think of JIT related methods like Kanban. However, the demands for flexibility, together with the limitations of the different control methods, suggest that an MRP based system be used.

The question is whether the MRP based systems of today are able to handle these demands on flexibility in practice. At the same time, the use of MRP systems is considered to build up on inventory levels and result in long lead-times. Furthermore, the incorrect uses of MRP, not the design differences, turn out to be the primary elements behind the deficiencies of MRP (Plenert, 1999a). This is where a closer look at the details of the AIP system is required. A decision as to where the flexibility is needed must be attained in order to apply the proper control principles at the right place.

The need for the entire production system to be flexible in many ways does not automatically entail for every single part of the factory has to be MRP controlled. Different methods are suitable for different tasks. Also, differences do exist between the MRP based software systems themselves, each exhibiting its own strengths and weaknesses (Estep, 1996; Gumaer, 1996; Schotten & Kees, 1995). In order to gain the required benefits, JIT methods will most likely be a well working alternative in many parts of the production, where the limitations are of little or no concern. Parts of the production will have a more stable order situation than the final assembly, which may give the opportunity to use, for example, Kanban control.

This brings the discussion to what must be considered when designing a PPC solution for AIP. First we have to realise that the control and planning will, to some extent, be individual to the specific company using AIP. The common denominator being that it will follow a certain pattern specified by the theory behind AIP. The individual stages of the system will be the pre-module assembly stages of the production.

The product and the modularisation of the product will very much put constraints on, for example, the possibilities of arranging machines into different layout types, i.e. cell production. Cells could be, for example, Kanban or CONWIP (Spearman et al, 1990) controlled internally and then be a single planning point in a higher-level MRP based system.

The suggested solution is a more decentralised control concept within the company with a more modular approach where each sub control system covers only a part of the production system. The expected benefits from such a system approach is that it provides departments with better opportunities to incorporate their specific planning requirements in the control system (Eeuwe & Wortmann, 1998). This would make the PPC system to support the inher-
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ent characteristics of AIP.

The issue of using single software based planning and control system versus using open systems, combining different program modules and functions needed, are of great concern. There are undoubtedly many advantages with the use of open systems and combining different function modules, such as a simpler tailoring of the system after the current production situation in a company (Drabble, 1998; Estep, 1996; Plenert, 1999a).

The large systems often cover a large number of activities including areas like system control, item master data, sales etc. The problem is that although they cover a wide range of functions, they do not deal with any of them deeply enough (Schotten and Kees, 1995). Customisation is the only manner to make them work deeply on an individual area.

One problem with tailoring a single large system is that it becomes very expensive and, in the end, become out of reach for smaller companies (Mustafa and Mejabi, 1999). This also speaks for the open solution, giving the smaller company the ability to start with one module and if needed upgrade with more functions from the same, or other, software companies.

The demands on the PPC system, using AIP production methods, could therefore be summed up as follows:

- There should be instant access to the current production situation. The system should work in real time needed data always is accurate. This is due to the need to be able to make quick changes in the schedule, to obtain the needed flexibility and to provide the organisation with a tool for planning and making decisions. In the customer-driven environment that AIP is a part of, manufacturers must be able to continuously revise their schedules based upon unplanned events. To accomplish this, their process and data models, information systems, and communications structure must operate seamlessly in real time (Gumaer, 1996).

- It has to be easily modified so that it always fits the current production. Using open systems that are stepwise expandable and adaptable to current situations, is a viable solution (Estep, 1996).

- Easy to use for all, otherwise people will stop using the system. This is especially true when handling rush orders and other rescheduling events, which often lead to loss of control on inventory levels, free capacity etc.

These three points form the framework for designing the PPC system principles for AIP. The description is a first attempt to organise solutions regarding PPC.
Figure 3.12 is a simplified drawing of a company using AIP. It consists of a final assembly station (A), module buffer (B), module workshops (C), three different types of part manufacturing (D, E and F), delivery from suppliers to
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material buffers (G), delivery from supplier directly to the module buffer (H), and finally delivery of finished product to customer (I). The entire factory will be controlled by a MRP based system due to the demands for flexibility, but also for the possibility of using an already existing PPC software system in an AIP-modified factory. As stated earlier, the system will have to work in real time and be easy to upgrade/modify. The final assembly (A) will receive its information from this system. The current order situation, available capacity and other information needed to place the order in the production chain will be available. The module workshops (C) will produce to the levels in the module buffer (B). The part manufacturing could be individually controlled, where the choice of principle or method could be chosen in consideration of the layout of the manufacturing. D, E and F could be considered to be cells with their own internal planning and control.

The figure describes three situations: D is a classical U-cell in which the production occurs in a specific manner. U-cells are usually easy to monitor and the material flow could, for example, be controlled by a Kanban system. This layout could be used when manufacturing a range of similar modules in greater numbers. If there are modules in lesser numbers and greater variety, the manufacturing could be arranged functionally (E). This is a typical environment for MRP control. In this case we could arrange virtual cells and use an appropriate type of JIT related method. F consists of two lines, joining in a final operation. If a bottleneck is identified, OPT could be a suitable approach (Goldratt & Cox, 1986).

The sub-contractors could, depending on the amount of delivered goods and their value, be incorporated into the planning system. They could even have people stationed within the factory, taking part in production meetings etc. This, however, requires a relatively large value of delivered goods, which, in many cases, could rule out smaller sub contractors in such an arrangement (Pragman, 1996). However, the more accurate predictions of required supplies will give the sub-contractors a more stable situation, which, in turn, makes it easier for them to deliver on time.

Production planning and control arranged in this manner simplify the delivery time predictions for a sales department, and, therefore, provide increased customer support. It will be possible to check the status of an entire order since the system works in real time and allows keeping track of the material and components that will be manufactured and assembled into the ordered goods.
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Figure 3.13: A structured view on which control method to use in different situations (Karmarkar, 1989).

This is one example on how to choose control methods for different situations (Karmarkar, 1989). AIP would be represented by **Pull: Continuous Flow**, or **Hybrid Push-Pull: Batch Repetitive**, depending on the situation. That is, if the implementation has been successful enough in transforming the high variability in customer orders to low variability in the manufacturing environment, including a low variability in lead-times.

Karmarkars (1989) reasoning supports the idea of having JIT based ordering methods within cells and groups and at the same time use an over all planning system, possibly MRP based. According to Karmarkar (1989), the common situation calls for some sort of pull-based ordering on the shop floor. The order release is to be executed according to order rate, that is rate based or JIT. The effectiveness of the involvement of MRP based PPC systems at this stage, depends highly of the quality of input data.
Since data quality is known to be low in many PPC systems (Karlsson & Strömberg, 1998; Karlsson, 1999), the involvement of approximate MRP data in order release should be avoided in such cases. Since improving accuracy of data in, for example, inventory levels and capacity levels, is a must for many reasons and should be conducted regardless of implementing AIP, MRP could become a viable solution. Material planning is to be executed according to JIT or hybrid JIT-MRP. Again, the quality of data becomes an issue.

An interesting observation made at the studied companies that also related to the manufacturing processes subject introduced earlier, is that an important part of the information flow follows the manufacturing flow. This could be made clear by looking at the Kanban manufacturing control method where information on the amount of components to be manufactured etc, is practically attached to the products. Summarising the results from the studies, one may come to the conclusion that the less information that follows the manufacturing flow, the less control is applied on the flow itself. This observation had to be refined somewhat, since it is too wide. There is for example, information not vital to the control function that does not provide any positive effects by following the manufacturing flow. Looking closer into the Kanban method which arguably is accurate, though not very flexible, helps refining the conclusion. In Kanban, information on what volumes to manufacture and when to execute the manufacturing operations is attached to the products. It also says where to send the manufactured goods and it orders material from the previous station in the manufacturing flow (Slack et al., 2001). This information is vital to the manufacturing control function. Most of the studied companies did not have such an information flow through the manufacturing, leaving the entire task of control, not applied by the MRP system, up to supervisors on the factory floor. Arguably, there is information that may be distributed by other means of transportation than by following a product through the flow, since it may have to be made available instantly. An example of such information is information on disturbances and available capacity.

It was also observed that the more structured the flow, the easier it was in practice to send information along with the products. This means in reality that in department layout factories, it was harder to maintain such an information flow than it was in a line layout.

The lack of use of Kanban type control systems was also notable during conducted interviews. It was considered to be too problematic to implement such control methods. The knowledge about such methods was however
rather limited. No information on CONWIP or different variations on combining Kanban and CONWIP was widely spread. It is possible that these approaches could have been useful solutions at some of the companies. The structure of a manufacturing where AIP has been implemented should provide clearer manufacturing flows or at least, a more structured factory compared to a department layout factory (see figure 3.3). This should make such implementation problems less significant.

3.4 Summarising AIP system requirements

Chapter 3 has served as an exposition on the areas that are subsets of production. It has also been a mapping of different theories and methods that could be used within AIP and also some aspects to have in mind when implementing AIP and conducting future research. A short review of notable points made when it comes to theories and methods, is in place here:

Materials supply:
- Supply Chain Management: Since SCM lacks a definite definition; it is not possible to include SCM as a component of AIP. SCM is certainly a research area to look into since it in many ways has the same goals as AIP.
- Lessen the impact of the bullwhip effect by using information distribution and creating short lead-times in the manufacturing.
- Third part logistics is a possibility when creating a transportation system that has the flexibility and capacity of the manufacturing system.

Information handling and use:
- Product Data Management has many possibilities usable within AIP, which makes it an area to develop.
- Production Planning and Control is an area of great importance that has many possible solutions. Possibilities are for example Kanban, CONWIP, OPT/TOC, MRP and combinations thereof.
- A modular approach when developing a computer based PPC system is argued for. This is to be able to adapt the PPC system to the structure of the actual manufacturing system.
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**Human resources in manufacturing:**
Here no specific methods are proposed. One should note that this does not reflect the importance of the subject. A lot of research done, when it comes to human issues, is valid within AIP. A special attention should be put on the effort of finding a suitable form of organisation for AIP.

**Manufacturing processes:**
- To manage short lead-times is of great importance. A reduction of time that does not add value to the product should be reduced, set-up times included. A method possibly to use is the SMED method.
- Flexibility is a building block of AIP, which is attained by working with the manufacturing processes in conjunction with product design. A solution when it comes to processes is the development of standardised interfaces between machinery so that automated equipment could be rearranged to create flows that fit the current order situation.

**Product design:**
- A modular product design is a part of the AIP strategy. A modularisation method available is Modular Function Deployment (MFD) (Erixon, 1998).
- Standardisation of parts is a goal.
- Use of Design For X, including Design For Manufacturing (DFM), Design For Assembly (DFA) and Design For Automatic Assembly (DFA2) (Eskilander, 2001).

Given the amount of factors to consider, a method structure is needed to be able to implement and use AIP as well as any other strategy aiming for high flexibility, short lead-times and high performance in general. The structure should also help in pointing out a set of suitable methods to use, as implied in this chapter. The enumeration of methods made in this thesis is not enough. People with knowledge in their respective area should choose appropriate methods.

**Observations important for future research**
During the AIP studies, causes for different kinds of disturbances and problems in manufacturing have been researched in order to be able to handle them. The results show that anything can cause trouble of different kinds. There
are examples in literature and from the surveys and case studies presented here of anything from people taking coffee breaks to accidents on highways and strikes on airports, causing delays. This could arguably call for the use of buffers and stored products in order to provide secure deliveries to customers. The development of flexible and reliable processes could however lessen the need for buffers and stored products.

Figure 3.14: The relationship between the different AIP research areas.

The research also shows that activities within one of the different areas, here defined as materials supply, human resources, manufacturing processes, product design and information handling and use, are affecting the other areas in different ways. The reason for it and the magnitude of the resulting effects may vary from situation to situation though. This was often observed during the studies.
Results part 2

Manufacturing system design method
A theory base for manufacturing system design
Chapter 4

As stated in chapter 1, one research goal with this project is to develop a manufacturing system design method. Chapter 4, 5 and 6 are devoted to explaining the development of the method and to the description of its use.

To make the understanding of the method easier, the explanation is divided into parts and presented in three chapters. In this chapter, a theory foundation for the proposed design method package is presented. Means for using the theory and putting it into a context is presented in chapter 5. In chapter 6, the theory and the structure is put together into a method description and usage details are explained. In the end of chapter 6, the method is critically reviewed and alternative solutions as well as continued method development are discussed.

4.1 Specifying manufacturing system design process tasks

The process of manufacturing system design and development is here considered to consist of four different stages, which are presented. The dividing into stages is useful when positioning the method in the process of manufacturing system design, showing the intended use. The intended use indicates what could be expected of the method; the outcome is not an optimal system design, but a first system draft. The dividing into stages are followed by the introduction and defining of basic concepts which are to be used when describing properties of manufacturing system solutions and requirements. The definition of the term concept and other related terms used is available in section 2.2.1.

4.1.1 Defining system development stages

The division into development stages is here shown in a figure. The figure contains more information than might be noticeable at first, which makes the following text crucial to fully understand it. After the figure, a short description of it is made, which then is followed by a description of each phase. It is recommended to return to the figure when reading about the phases.
A theory base for manufacturing system design

Figure 4.1: Different design phases as defined and used in this thesis, including operation and continuous development. The term strategy is defined in section 1.1.

Input data for the first designs could originate from an entirely new draft or build upon an existing earlier system. After having established general system requirements in phase 1, one enters the first real design phase, phase 2, where the first system draft is put together. It is in this phase where the proposed method is intended to be used. In the next phase, phase 3, there is a system concept to evaluate, being it virtual or a first design. Here, one could more easily find methods to evaluate the design and improve it.
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Notable is that this phase is almost identical to when the system is in use. Many improvement methods could be used and the philosophy of continuous improvement highly established in manufacturing operations is quite similar to design improvement. Therefore a model that relies upon relevant data could be used, both in the system design phase and the use phase.

The operational phase, phase 4, includes issues that are relevant when operating the system, including continuous improvement, service etc. Even though being a highly researched area in the AIP related work, phase 4 is mostly left out hereafter due to the project delimitations presented in chapter 1. Phase 1 is also not discussed deeper, since they are outside the scope of this thesis as well.

The reason for enabling a division into phases is that at this stage the goal is to accomplish a model of a manufacturing system accurate enough for continued development. Hence, to be able to find relevant factors and their magnitude to work with further - not to assume even before the model has been assembled, what the relevant issues are.

Establishing requirements, phase 1

As stated earlier, the working procedures of phase 1 have been left out. Important to remember is the purpose of the work in this phase. Here, the requirements of the manufacturing system is established, using market data, economical goals etc, creating demands specific for the intended manufacturing system. The requirements are input data for the next phase.

Development of a first system model, phase 2

The early design phase is when one does not have any earlier systems to build upon, for example models or actual plants, meaning having to start from a clean sheet when one has to create a first model of how to accomplish the demands put on the system.

There are many options on how to conduct the phase 2 design work and in figure 4.1 two basic variants are mentioned. Strategies are often used. In such cases, the information tells the users what to aim for rather than what detailed solutions would be suitable. Another possibility is using a methodological approach based on comparing sub-system characteristics and the
desired manufacturing system characteristics. Sub-systems are manufac-
turing system solutions, i.e. different kinds of machinery, factory floor layout
solutions, production planning and control system properties and working
procedures.

Figure 4.2: Only illustrating phase 2

In figure 4.2, a more detailed view on the intended order of procedure is
presented, using required properties and available sub-system properties as a
base. The procedure starts with defining the desired system properties. This
is conducted by examining the established requirements put on the manufac-
turing system, decided in phase 1. Then, the properties are to be described in
measurable terms or general performance measurements. These general
measurements are then compared to the performance of available system
solutions. Thereafter, a first system solution is created, which finalises the
work in phase 2.

This operating procedure means approaching the solution from two direc-
tions, from the system solution side and from the general demand side,
leaving a need for a set of common parameters applicable on both sides. The
development of such a set of parameters is presented in the rest of this
chapter but particularly in section 4.5. The emphasis of the work in chapter 4
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is within methods based on characteristics.

**Further development of the system model, phase 3**

The late design phase is defined as being the period when a model is already available for further improvement. As argued for in chapter 1, there are many manufacturing related means available for working within this phase including different ways of simulation, methods for lowering waste of time (e.g. Kanban control), making products easier to manufacture (e.g. DFA, DFM), improve organisational structures etc, using the input data which is the first system model. It is possible to compare different suggested solutions with each other and improving them until there is a solution available that meets company demands.

**The operational system phase, phase 4**

In this phase, there is a manufacturing system available, either ready to operate or in operation. There are however, striking similarities between the operational system phase and the late design phase when it comes to evaluating the system design. The benefits with continuous improvement have been an issue within the manufacturing community for many years (Womack et al, 1990). Using a model of the manufacturing system to find areas for improvement is very similar to the work for improving an early model in the late design phase. One has to note the difference in obtaining data for the model though. In the operational phase, the data would be retrieved from the real manufacturing system. In the late design phase, the data would most likely be calculated from a virtual model.

**4.1.2 Using system and solution properties as a base**

During the pre-study research phase (presented in chapter 3), demands were identified for a system design method or system design guidelines, providing a serial work order solution, much like a cookbook. During the initial project meetings, an opinion highly argued for was: there are a lot of methods, philosophies and strategies available, useful in different situations, as means for accomplishing competitive manufacturing. Mentioned were for example,
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Just In Time, Kanban control method and cell manufacturing.

The problem is that they are stated to be good, effective, efficient etc, but there are few methodological approaches on when and how to use them.

Looking at figure 4.1 and the description of the different system development phases, this problem could be identified as a lack of methods for use in phase 2. The load of methods available, some mentioned at the project meetings, are mainly used in phase 3. Philosophies and strategies ranges from phase 1 and downwards, but do not provide enough guidance for conducting explicit design work in phase 2. Expressing the properties of the means in measurable parameters would assist in choosing the correct methods and possibly strategies.

When starting the AIP project and going through the project goals, there was a consensus on some demands on the method to be developed:

- It should give clearer guidelines on what to do and aim for than the presently available strategies and philosophies.
- It has to be possible to use in a structured way and the work order should be specified in the method.

It can be identified in these demands that there is a need for a general design method, providing guidelines on what methods to use when developing different sub-systems in the manufacturing system. The demands also indicate the need for a methodological approach based on system characteristics rather than just providing a table of useful methods, either as a complement to, or preferably as a replacement for the use of strategies. The suggested approach depicted in figure 4.1 and 4.2, is intended to work in that way. A possible approach would be to suggest appropriate methods already available, to use when designing manufacturing systems, since there are many that are used and proven over time. The reason for not suggesting available methods is the continuous development in the field of designing and improving sub-systems. If a suggested method is replaced by a new one, or proven to be incorrect, the general design method would become weakened or useless.

There is also the problem of implementing and using single solutions without knowing exactly why, which has been discussed in section 1.1. Since one of two goals with this research is to develop a general method for use within the early design phase of manufacturing system development, the route of recommending specific solutions will not be used. Instead, the method is being based on requirements and solution properties.
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Finding key properties that an improvement or design method should have is preferable, since a better method could then be chosen instead of the worse. The general design method is not dependent on a single sub-method, it merely provides the properties needed from that method.

To be able to use manufacturing solution properties, the sought-after properties of different solutions should be researched and examined. Examples of manufacturing system design solutions are the Kanban and Conwip control methods, using cell layouts and using automated equipment. An in-depth review of what Kanban, Conwip etc. is actually doing in the sense of actual operations is not enough in this case.

In the suggested method, the system design solutions should be evaluated according to the same concepts and units as used when describing system requirements. In this way, there should be a standardised seamless connection between requirements and solutions. Defining concepts useful for describing requirements as well as system solutions is therefore an important part of the development of the proposed general manufacturing system design method.

4.1.3 Comments on the research approach

To predict what effects different changes made to sub-systems in a larger manufacturing system would have on the performance of the manufacturing system as a whole could be difficult. Therefore an additional goal, shown as partial research goal D in figure 1.2 in section 1.2.3, became the development of a general method structure and performance parameters that could describe the performance of a manufacturing system, regardless of development phase and organisational level. This would make the outcome of using the method, the first system model, more compatible with phase 3 methods. There is no need for the resulting design method (presented in chapter 4, 5 and 6) to give exact results, since it is placed mainly in phase 2. There are many methods that could be used to improve on the first design, in phase 3. The proposed method should give a correct and an accurate enough structure to improve.

The working structure of the method has formed a base for the rest of the research. The method components are presented in the following sections and argued for accordingly. The rest of chapter 4 is structured, beginning with general discussions from the higher-level performance measurement
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side of operations, covering higher-level performance measurement factors in order to be able to link them to the suggested concepts describing system properties.

Section 4.3 is dedicated to presenting guidelines, which should be taken into account when deciding what concepts to use when describing system properties. The base is scientific guidelines for what to use and how to use it in performance measurement. Of high importance is the discussion on the probability of maintaining accurate parameter values through the use of the method.

Data and experience from the larger case studies and surveys presented in chapter 3, has been used to a large extent when researching the topics presented in chapter 4. In some instances, more detailed data was needed to answer specific questions regarding topics brought forth in the chapters 4-6. Therefore additional case studies have been conducted. The questions to be answered by the case studies were in many cases identical to the ones asked in the development of a factory floor control system, presented in chapter 7. The reason for the similarities is the sharing of components between the manufacturing system design method and the control method. Therefore, case studies covering chapter 4-7 were conducted in parallel.

4.2 The performance of manufacturing systems

In this section, common issues, related to the evaluation of manufacturing system performance are presented. There are numerous articles written about performance measurement and performance measurement systems (PMS), but a large percentage of it covers manufacturing at a higher level than the one intended in the proposed design method, which does not include a PMS system. The reason for bringing it up is to make the measures used in the method, compatible with available performance measurement systems and higher levels of planning in a manufacturing company.

The definition of the term performance will cause significant trouble if not proceeding cautiously. In general, in this thesis performance is derived from the verb perform. Perform means to do (an action or piece of work). Performance of a person or a machine is how well they do a piece of work or activity (Cambridge, 2002). Performance is usually used in this sense for
most of the thesis. In management and operations research however, performance has a somewhat different and more specified meaning. This meaning is presented and explained in 4.2.1 and used accordingly for the rest of section 4.2.

There is a term, performance measurement (PM), which is related to the latter definition of performance. It is also explained in section 4.2.1. PM will be used in this sense for the rest of chapter 4. If performance measurement is used in another meaning, it will be emphasised and the abbreviation PM will not be used.

4.2.1 Performance, productivity and profitability

Performance is stated by many to be a topic with a wide range of different definitions. The general definition of performance actually makes the process of measuring performance very general in itself. A central part of performance is cost, but there are also many other components involved. These components are often related to the behaviour of a manufacturing system.

Inadequately designed performance measures can result in dysfunctional behaviour, often because the method of calculating performance (the formula) encourages individuals to pursue inappropriate courses of action. Designing a performance measure involves much more than simply specifying a robust formula. For issues such as the purpose of the measure, the frequency of measurement and the source of data all have to be considered (Neely et al, 1997). Since the goal is to develop a manufacturing system design method, it would be most unfortunate if it encourages dysfunctional behaviour of the resulting manufacturing system. Therefore, the choice of performance measures is of outmost importance.

Performance measures are closely linked to what is often called productivity and profitability measures and rations. According to Neely et al (1995):

- Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action.
- A performance measure can be defined as a metric used to quantify the efficiency and or effectiveness of an action.
- A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions.

To make matters somewhat more complicated, there are many definitions of
A theory base for manufacturing system design

efficiency and effectiveness. Some are relatively similar, with the difference being which concepts and units that are used to measure it. Efficiency and effectiveness are central terms in PM, related to doing things right and doing the right things.

Figure 4.3: General definitions of efficiency and effectiveness (Tangen, 2002).

Productivity could be seen as a function of efficiency and effectiveness.

Figure 4.4: Productivity is generally defined as a ratio of output to input of the manufacturing transformation process (Tangen, 2002).

The term productivity is here defined as the relation between output and input. This definition leaves options on choosing what should represent input and output.

Figure 4.5: Profitability is strongly influenced by the prices a company pays for its input and receives for its outputs (Tangen, 2002).
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Profitability is defined by using figure 4.6. Profitability is generally defined as a ration between revenue and cost. Hence, being very reliant on market trends situations. Profitability could be seen as productivity with components added that includes costs and revenue.

One can see that many manufacturing related variables are involved in what is defined as performance measurement (PM). Since the proposed method is positioned in an early design phase, much of the data related to PM is still unknown at the time of use. Cost and revenue related parameters are left out because of this, which does not mean that they are unimportant. They should of course be taken into account, but at another stage, when costs for machinery, personnel etc are known. Therefore PM issues are aimed towards shop floor activities that could be decided at an early design stage.

4.2.2 From PM towards factory floor parameters

Slack et al (2001) describe five performance objectives to aim for. The need for them is said to be subject to variations over time due to for example, customer requirements.

- The quality objective: one wants to do things right. Examples of good quality are that all parts are made to specification, the product is reliable and the product is attractive. What is needed to do things right will vary according to the type of operation.

- The speed objective: one wants to do things fast. Speed is important inside and outside the operation. Outside, the customer has to wait for the product. Inside, speed is essential to keep inventories down, simplify planning etc.

- The dependability objective: one wants to do things on time. This gives predictability, which is useful for example, to simplify planning, to reduce stops due to lack of parts etc.

- The flexibility objective: one would want to change what one does. There are needs to be able to vary or adapt the operations activities to cope with unexpected circumstances or to give customers individual demands. Flexibility is discussed more in detail later on.

- The cost objective: one would want to do things cheaply. This includes for example, producing goods and services so that they could be priced competitively and still making profit. Since the process of calculating costs is outside the scope of the method package, it has very much been left out. It could
however, be done in parallel to or just after applying the method package in a design project.

There are other different PM related categorisations available. One is the division of performance measures into two categories: results (competitiveness, financial performance) and those focusing on determinants of the result (quality, flexibility, resource utilisation and innovation) (Fitzgerald et al, 1991). Wisner & Fawsett (1991) uses quality, cost, flexibility, dependability and innovation as improvement directions for use within the manufacturing function.
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<table>
<thead>
<tr>
<th>Performance objective</th>
<th>Some typical measures</th>
</tr>
</thead>
</table>
| Quality               | Number of defects per unit  
                          | Level of customer complaints  
                          | Scrap level  
                          | Warranty claims  
                          | Mean time between failures  
                          | Customer satisfaction score |
| Speed                 | Customer query time  
                          | Order lead time  
                          | Frequency of delivery  
                          | Actual versus theoretical throughput time  
                          | Cycle time |
| Dependability         | Percentage of orders delivered late  
                          | Average lateness of orders  
                          | Proportion of products in stock  
                          | Mean deviation from promised arrival  
                          | Schedule adherence |
| Flexibility           | Time needed to develop new products/services  
                          | Range of products/services  
                          | Machine change-over time  
                          | Average batch size  
                          | Time to increase activity rate  
                          | Average capacity/maximum capacity  
                          | Time to change schedules |
| Cost                  | Minimum delivery time/average delivery time  
                          | Variance against budget  
                          | Utilisation of resources  
                          | Labour productivity  
                          | Added value  
                          | Efficiency  
                          | Cost per operation hour |

*Figure 4.6: Some typical measures of performance (Slack et al, 2001).*

Figure 4.6 shows the nature of some performance measurements suggested by Slack et al (2001). Notable is that the suggested typical measures is of different nature, including direct time measures, monetary measures, frequencies, scores of different kinds etc.
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<table>
<thead>
<tr>
<th>Performance objective</th>
<th>Some typical measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality</td>
<td>% defect reduction</td>
</tr>
<tr>
<td></td>
<td>% scrap value reduction</td>
</tr>
<tr>
<td></td>
<td>% product returns or warranty claims reduction</td>
</tr>
<tr>
<td></td>
<td>% unscheduled downtime reduction</td>
</tr>
<tr>
<td></td>
<td>% supplier reduction</td>
</tr>
<tr>
<td></td>
<td>% of inspection operations eliminated</td>
</tr>
<tr>
<td></td>
<td>% time reduction between detection and correction</td>
</tr>
<tr>
<td>Cost</td>
<td>% inventory turnover increase</td>
</tr>
<tr>
<td></td>
<td>% average setup time improvement per product line</td>
</tr>
<tr>
<td></td>
<td>Total product cost as a function of lead time</td>
</tr>
<tr>
<td></td>
<td>% reduction of employee turnover</td>
</tr>
<tr>
<td></td>
<td>% reduction in total number of data transactions per product</td>
</tr>
<tr>
<td></td>
<td>% improvement in labor/desired labor</td>
</tr>
<tr>
<td>Flexibility</td>
<td>% increase in average number of direct labor skills</td>
</tr>
<tr>
<td></td>
<td>% average lot size reduction</td>
</tr>
<tr>
<td></td>
<td>% decrease in number of bottleneck workcenters</td>
</tr>
<tr>
<td></td>
<td>% increase in vendor inputs available in X days or less</td>
</tr>
<tr>
<td></td>
<td>% increase in multipurpose equipment</td>
</tr>
<tr>
<td></td>
<td>% increase in portion of product made for which a specified level of slack time exists</td>
</tr>
<tr>
<td>Dependability</td>
<td>% reduction in lead time per product line</td>
</tr>
<tr>
<td></td>
<td>% reduction in average service turnaround per warranty claim</td>
</tr>
<tr>
<td></td>
<td>% increase in portion of delivery promises met</td>
</tr>
<tr>
<td></td>
<td>% reduction in purchasing lead time</td>
</tr>
<tr>
<td></td>
<td>% improvement in output/desired output</td>
</tr>
<tr>
<td>Innovation</td>
<td>% increase in annual investment in new product and process research and design</td>
</tr>
<tr>
<td></td>
<td>% reduction in material travel time between workcenters</td>
</tr>
<tr>
<td></td>
<td>% increase in annual number of new product introductions</td>
</tr>
<tr>
<td></td>
<td>% increase in common parts per product</td>
</tr>
</tbody>
</table>

Figure 4.7: Performance criteria that link firm strategy to operating decisions (Wisner & Fawsett, 1991).

Wisner & Fawsett (1991) also suggest performance measures related to their definition of improvement directions for use within the manufacturing function. All but one are percentages.
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It would be desirable for the developed method to be compatible with this type of performance measurements in order to accomplish a seamless transition from corporate goals to factory floor related performance goals. Instead of incorporating as many of them as possible, they are broken down into components. These components are compared to those basic performance related components that are retrievable from a manufacturing system or a manufacturing system model.

4.3 Guidelines for selecting design concepts

The concepts that are to be used for describing system properties are of utmost importance in the aspects of choice and how they are designed. Otherwise, the resulting manufacturing system design could be useless. Therefore it is important to research and clarify certain guidelines and important factors to take into account when choosing and designing the basic concepts. Considered here are general guidelines, applicable in situations when the goal is to achieve accuracy results.

4.3.1 General guidelines

A first suggestion about choosing the right parameters for performance measurement is that they should preferably be based upon measures directly connected to operations goals and not the means to reach the goals. Measuring means could give less accurate values than measuring goals. The level of lost accuracy would obviously be different from case to case. They could be related to technical issues, behavioural issues, physics etc. It is possible that the actions taken to accomplish a goal, affect areas other than the one intended for improvement. This also makes it possible that there are other factors, affecting the reaching of the goal. The measurement of the means is also not necessarily directly linked to the results from trying to reach the goal. As another example, one could use a car. By experiments, one would find the relationship between the speed of the car and the fuel consumption, given certain conditions. Yet, there are few speedometers that use the fuel consumption as main source for information. Ignoring purely traditional
reasons for this, the accuracy would be dependent on the specified condition as well as more, maybe unknown, variables and uncertainties. The fuel consumption varies with for example, gear chosen at the moment, quality of tires, air temperature etc. In short, there are often many uncertainties between the goal (here measuring speed) and the means to reach them, especially when the conditions may vary. The probability of getting more accurate readings would be better if one measured the speed, for example by measuring the rotation of a wheel (a measurement closer to the goal) or by measuring the time taken to cover a certain distance (the measurement closest to the goal given the definition of speed). This reasoning is supported in theory by Axiom #2 in the Axiomatic Design method (Suh, 1990). Axiom #2 states that a solution with less information content than another, is a better solution since it has a greater probability of success. Measuring speed indirectly by measuring fuel consumption would be a solution with more information content than measuring time and distance directly.

Karlebo (1992) presents a classification of measurement errors that could occur due to the design of the mean for carrying out the measurement as well as for its use:

- Coarse errors, which occurs due to carelessness or serious interruptions, often rendering the measurement unreasonable in one way or another.
- Systematic errors, originating from for example, the measuring instrument or apparatus. It is possible to use corrections to lessen the impact of systematic errors. When adding or subtracting measures, the systematic errors are added or subtracted as well.
- Temporary errors could vary in terms of size and character and cannot be handled by using corrections.

Minimising the occurrence and the consequences of such errors is desirable.

There is also the phenomenon occurring when working with mathematical functions or models called error propagation. If a measurement is not directly available, it has to be calculated, possibly by using several measurements, all of them afflicted with errors of different kinds and degrees (Karlebo, 1992). The errors will be amplified or possibly, temporarily be levelled out (Pohl, 1995), affecting the accuracy of the originally sought after measurement.

Pohl (1995) presents sources of errors, used in numerical methods for scientific and engineering problems. Two of them are of particular interest when evaluating manufacturing system performance: incorrect input data
and incorrectly performed calculations, especially when coupled to the error propagation. Errors in used data will obviously propagate to output data in different ways and inaccurate models will result in even more inaccurate output data. Hence, it is very important to retrieve accurate manufacturing related data for using in the models and the models should obviously be accurate in its design. It is also important to know in what way input data errors affect output data error through error propagation. One should remember that error propagation is a phenomenon that occurs event though the model is correct.

If the mathematical function or used model is of an unfortunate design or the problem is defined badly, it will result in unnaturally large fluctuations in the error propagation, giving highly inaccurate end results.

The problem to solve could also be defined badly, causing inaccuracies in the end result.

Figure 4.8: A badly defined problem, causing possible inaccurate values when measured. In this case, it is hard to see where the intersection to be measured is situated (Pohl, 1995).

If for example, the problem calls for measurements that are hard to carry out, it may not be defined well (comparable to axiom 2 in AxD). To receive accurate results, both the problem definition and the algorithms have to be well conditioned (Pohl, 1995).

The following conclusions regarding factory floor performance measurements are made:

- The measurement should be correlated to the desired property of the manufacturing system.

- When it comes to measuring manufacturing system performance, measuring closer to the goal related concepts instead of concepts related to the means to accomplish the goals (equivalent to the examples given) would be desirable.

- Possible unknowns should be searched for and taken into account including possible types of error.
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- The accuracy of the initial measurement should be considered when calculating higher-level performance measurements due to error propagation.
- Measurements should be well designed to be easy to carry out, giving higher possibilities to end up right (see figure 4.8).

4.3.2 Deciding a basic property of the concepts

Scanning through research papers, it is common to find general development solutions or methods, recommending specific lower level methods as parts of a general solution. In manufacturing strategy research, a notable example is the recommendations to directly implement a certain type of factory floor layout or manufacturing control method like Kanban. For example, studies of Toyota Production System (TPS) may highlight different specific solutions and missing out details about the studied situation in which TPS has been implemented, making the process of coming to conclusions erratic to say the least. Using the Kanban control system as an example, there are many researchers stating that it is a way of improving manufacturing efficiencies, reducing waste etc. If one fails to arrange prerequisites for the implementation of Kanban, the method could be useless for others to implement, leaving the impression that TPS related activities are useless in general.

This is a very notable opinion among personnel responsible for manufacturing system development within companies (among others: Karlsson, 2001). An opinion by the same people, that the own company is of a unique nature, requiring unique solutions, could very much originate from this kind of thinking. If being an incorrect assumption, it could lead to the missing out of available and useful solutions. Others would often, almost automatically, disregard this belief of the uniqueness of the own company as an incorrect assumption for many different reasons. This difference in opinion should not be dismissed easily. It could well be that they are both correct, given a present situation. There are a few points that should be noticed, that are central to the rest of the discussion.

- Stating that a specific method is an ever working or even optimal solution to a specific problem is dangerous. New and better methods could be developed. New possibilities in other related fields that also affect the problem could emerge.
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- The belief in the uniqueness of the own company and the need for unique solutions could be correct.
- The belief that a standard solution is the best solution could be correct.
- A combination of the two above could be correct at different locations within a factory.

These four points makes it necessary to have access to knowledge about numerous factors as well as help to structure this knowledge.

4.4 Proposing and analysing concepts

The outline for the developed method states that it is necessary to use the same concepts and units for specifying manufacturing system requirements and manufacturing system design solutions. Therefore, technical solutions have been studied in a larger case study involving five companies. Results from the case are used when selecting concepts and units. The main reason was to establish what kinds of measurements that are used in different situations, at a lower factory floor or technical system level.

The results from the case study were used to decide and define basic parameters, based on the information presented in sections 4.1, 4.2 and 4.3. The concepts should be able to describe a manufacturing system well enough for it to make up a model useful in development phase 2. The concepts presented are based on the main components in the information retrieval and handling in different companies and on manufacturing events and situations. Suitable units are also introduced and discussed.

4.4.1 Suggesting basic concepts and units

In the field of manufacturing research, there is a need for basic physical quantities and units that could be used when describing the properties of a manufacturing system. The reason for this is argued for in different parts of this chapter. Concepts and units are therefore defined in this section, to be used in that role. It should be noted that the definitions are in some cases contradictory to definitions made by other researchers, but the need for the defined units is argued for, as well as the logic in defining them differently. Some of the concepts are barely useful as performance measures in their

The definition of concepts is available in section 2.2.1.
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basic form. They should instead be seen as building blocks for higher-level concepts. The concepts are chosen according to the scientific guidelines presented in section 4.3. They should be easy to measure with good accuracy, directly in a manufacturing system. If not directly measurable, it should be possible to calculate them with good accuracy. The concepts are also closely related to the performance issues intended to measure, being closely correlated to performance related factors. This is important, especially in higher-level concepts. Low-level concepts are by their nature, closely related to the problem since there are not many things that could be measured practically. Time, length and number of objects are examples of directly measurable concepts. Flexibility is not directly measurable, but possible to calculate, since it has to take more measurements into account as parameters in the calculation. High-level performance measurements could, if not being careful, become less correlated to the initial problem. The concepts are often also parts of higher-level performance measures, like the ones suggested by Slack et al (2001) in figure 4.7 and by Wisner & Fawsett (1991) in figure 4.8. The definitions of productivity, efficiency and effectiveness have also been taken into account when suggesting the following concepts.

**Item or not item**
This concept is used more as a part of other concepts than a standalone entity. It is however, quite useful. Looking at, for example, the Dagab case (for details, see appendix 1), a large part of the system control is based on detecting if there is a product present at a certain location or not. It is a simple concept, powerful in the sense of the possibilities in using it for calculation of performance measures, and later, for manufacturing control.

The nature of this concept is defined as Boolean; it is either true or false.

This concept is here called a first level concept since it is directly measured and not calculated from other measurements.

I = 1 or 0, 1 = true and 0 = false.

**Time**
Time is here defined as an actual time reading, read from a clock. It has no unit and would mostly be used for calculation or comparison with other concepts. Time is also considered a first level concept.

T = a specific time reading, for example 12.03.12.

**Lead-time**
Lead-time is the difference between two time readings, describing for example, the time taken through a process. Lead-time is considered to be a
second level concept since it is calculated by using different time readings. It could also be measured by starting a time reading from zero by using a stopwatch or similar.

$T_L = T_2 - T_1$. The unit is an appropriate time unit, for example seconds.

**Value adding time**

Value adding time is originally a high level concept since it takes many different parameters into account. It is defined as time spent on taking the manufactured products closer to the end goal. Hence, many factors could be involved in this concept. As stated earlier, this is an early design phase when a first system model is being built. Therefore, many factors, normally associated with value adding time are not known. Therefore it is defined as the difference between the lead-time and the time when actual manufacturing is taking place within a working unit like a machine or an assembly station. Value adding time is defined as a second level concept.

$T_{VA}$: Value adding time

$T_A$: Time when something is processed in a manufacturing unit, action time.

$T_{VA} = T_L - T_A$. The unit is an appropriate time unit, for example seconds.

**Quality**

Quality is very similar to the item-not item concept. The difference is the cause of the resulting value of the concept. The difference is that it is coupled to the reason why an item is not present. The definition is of statistical uncertainty. It is harder to calculate than the others, including a mathematically defined uncertainty. Since different processes have different probabilities of success, the function is not possible to specify mathematically here. It has to be specified for each case individually. Being defined as a percentage, quality is of a higher level than any of the other concepts presented in this section.

$Q_p = \text{the chance for a product to be present at a specified location. It is a percentage.}$

**Volume**

Volume could be a number of manufactured units of a volume measure like litre. In the case of industrial manufacturing, it would most often be used as a number of products. It is a second level concept since it is calculated by using differences in measurements of the unit-not unit concept.

$V = \text{volume. The unit could be a number or an appropriate volume measure like litre}$
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**Capacity**
Capacity: the total amount that could be contained or produced, or the ability to do a particular thing (Cambridge, 2002).

Capacity is here used in the former meaning. It is the concept used for describing the number of products manufactured per time unit. It is considered to be a velocity to its nature.

\[ C = \frac{V}{t}, \text{ volume per time unit. Another definition is } C = \frac{dV}{dt}. \]

The nature of capacity is discussed in section 4.6.2.

**Adaptability**
Adapt: to change (something or yourself) to suit different conditions or uses (Cambridge, 2002).

Adaptability is a concept, related to the possibility of change in a manufacturing process. It is used here as a measurement on whether it is possible to adapt a process to new circumstances or not. Hence, it is of Boolean nature.

The adaptability would in many cases be dependent on many factors, for example cost. If money would be unlimited, it is likely that it would be possible to adapt any process to any circumstances.

\[ A_D = 1 \text{ or } 0, \text{ 1 if it is possible to adapt the process, 0 if it is not.} \]

**Agility**
Agility: able to move about quickly and easily, nimble (Cambridge, 2002).

Agility is used in the sense of speed of change. It is considered to be an acceleration phenomenon.

\[ A_G = \frac{dC}{dt} \text{ or } \frac{d^2V}{dt^2}, \text{ the unit would therefore be } \frac{V}{t^2}. \]

This could be a rather unpractical unit to use in practice. Instead one may use time to accomplish a decided change, which would give it an appropriate time unit. For example, seconds.

**Flexibility**
Flexible: changeable, able to change or be changed easily according to the situation (Cambridge, 2002).

Flexibility is defined as the product of adaptability and agility, thus being a function of them both. It is a measure of the changeability.

It could be impossible to make changes \((A_D = 0)\), but if it is not \((A_D = 1)\), how quickly will we change?
Chapter 4

\[ F = A_d \times A_c \]. The unit will be the same as for agility since adaptability is a number.

**Figure 4.9:** The nature of flexibility, being a function of agility and adaptability.

### 4.4.2 Analysis of the concepts capacity and flexibility

Recapitulating the definition of capacity, presented in section 4.6.1, capacity is highly coupled to the number of operations that are planned to be performed within a specified time frame. The number of products to be manufactured could be translated into operations, being a part of a larger manufacturing process. Even though capacity is here measured in manufactured units per time-unit, e.g., products/hour, it is important to remember this coupling. It is the main reason why the product design affects the theoretical maximum capacity.

**Figure 4.10:** The difference between the theoretical maximum capacity and the real capacity, actually available.
There is a difference between the capacity that is possible to utilise and the maximum capacity, theoretically possible accomplishable. The difference come from all kinds of sources, for example unplanned break-downs, delayed material deliveries, inaccurate information etc. Numerous sources for this difference have been found during the pre-study phase as well as more focused surveys and case studies (presented mainly in Karlsson, 2001; Karlsson & Grünberg, 2002; Karlsson & Halonen, 2002).

The theoretical maximum capacity \( (C_{TM}) \) could however, be rather easily defined as being decided by:

- The speed and reliability of the manufacturing processes. Standstill due to resetting etc is considered to be an issue related to the real capacity.
- The speed and reliability of the people directly involved with the manufacturing processes.
- The amount of parts to be manufactured.
- The ease of which the parts may be manufactured (e.g. DFA-index, materials data etc).

In other words: it is the performance of a process when being run flat out, without any disturbances of any kind. That is, the \( C_{TM} \) is decided by the resources directly involved in the manufacturing processes and by the product design. The \( C_{TM} \) is an ideal situation with no shortages and no unexpected occurring events. \( C_{TM} \) also implies no affecting setup-times.

\[ \text{Physical unit/time unit} \]

\[ \text{Theoretical maximum capacity} \]

\[ \text{Real capacity} \]

\[ \text{Figure 4.11: Defining waste as the difference between } C_{TM} \text{ and } C_{RU}. \]

The difference between the real capacity that could be utilised \( (C_{RU}) \) and the \( C_{TM} \) is called waste in the production philosophy Lean Production. The arrow in the figure above shows the difference considered to be waste.
Figure 4.12: Increasing the $C_{TM}$ do not necessarily affect the $C_{RU}$.

To be able to increase the level of the $C_{TM}$, one has to work with the design and composition of the manufacturing system and/or the product design. $C_{TM}$ improvements are done by:

- Increasing the speed and the accuracy of the manufacturing processes and the people directly involved with them.
- Designing the products according to certain guidelines (standardisation, Design For Manufacturing, Design For Assembly, product modularisation).

Hence no improvements in materials supply, information handling or indirect human resources can contribute to an increase of the $C_{TM}$.

Notable is that an increased $C_{TM}$ level does not necessarily increase the $C_{RU}$ level. One has to remember that the difference between $C_{TM}$ and $C_{RU}$ is not a fixed number. For example, if one increases the $C_{TM}$ by introducing a new faster NC machine in a flow, there is absolutely no guarantee that the $C_{RU}$ level will move, and if moving, by how much. There is even a possibility that the $C_{RU}$ level could decrease.

Figure 4.13: Increasing both the $C_{RU}$ and $C_{TM}$ could result in a large total capacity increase.

Since the $C_{RU}$ represents the available capacity, it is important to work with improvements in all areas to be able to get results that are useful in the manufacturing as a whole. An increased $C_{TM}$ together with reduced waste could make great changes to the $C_{RU}$.

Work aimed at increasing $C_{TM}$ could reduce waste and vice versa. For example, by designing the product according to a DFA method reduces the part complexity as well as the number of parts. This will increase the speed of the processes since there are fewer details to assemble but it will also reduce the
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amount of work one has to put into administration. Fewer parts means fewer article numbers to administrate and to keep track on, to keep the inventory levels on, etc.

The difference between maximum capacity and real capacity utilised could be used as a performance measurement. It is equivalent to the definition of effectiveness given in section 4.3.1, connecting these factory floor level measurements to higher-level performance measurements.

Calculating levels of flexibility as presented in section 4.6.1, makes it possible to replace capacity with flexibility in the reasoning above, giving a maximum flexibility and a real flexibility utilised. System factors that result in flexibility are sometimes hard to decide as of their nature and degree. One could argue that if only the process is provided with means to manufacture products (i.e. material, operators and energy), the deciding factors would be the maximum flexibility permitted by the product design and of the machinery. The reasoning is equivalent of the one conducted with capacity. This would make flexibility a feasible performance measure as well.

4.4.3 Positioning present flexibility definitions in a context

Flexibility is a somewhat controversial topic with many different definitions available. Therefore, the definitions made earlier are here presented and related to already available definitions.

The goal with flexibility in a manufacturing system is to measure the changeability of the system. There are many different definitions of flexibility available; many of them related to different system related factors affecting the overall flexibility of the system.
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<table>
<thead>
<tr>
<th>Flexibility type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routing flexibility</td>
<td>Gerwin, 1983; Browne et al, 1984</td>
</tr>
<tr>
<td>Material flexibility</td>
<td>Gerwin, 1983</td>
</tr>
<tr>
<td>Operation flexibility</td>
<td>Browne et al, 1984</td>
</tr>
<tr>
<td>Volume flexibility</td>
<td>Gerwin, 1983; Browne et al, 1984</td>
</tr>
<tr>
<td>Machine flexibility</td>
<td>Browne et al, 1984</td>
</tr>
<tr>
<td>Process flexibility</td>
<td>Browne et al, 1984</td>
</tr>
<tr>
<td>Production flexibility</td>
<td>Browne et al, 1984</td>
</tr>
<tr>
<td>Capacity flexibility</td>
<td>Tichem, 2000</td>
</tr>
<tr>
<td>Interior flexibility</td>
<td>Johansson, 1981</td>
</tr>
<tr>
<td>Batch flexibility</td>
<td>Landqvist &amp; Papinski, 1983</td>
</tr>
<tr>
<td>Unplanned changes flexibility</td>
<td>Andreasen &amp; Ahm, 1986</td>
</tr>
<tr>
<td>Product flexibility</td>
<td>Chryssolouris, 1996</td>
</tr>
<tr>
<td>Re-use flexibility</td>
<td>Björkman, 1990; Bodine, 1993</td>
</tr>
<tr>
<td>Design flexibility</td>
<td>Andreasen &amp; Ahm, 1986</td>
</tr>
<tr>
<td>Mix flexibility</td>
<td>Gerwin, 1983</td>
</tr>
<tr>
<td>Expansion flexibility</td>
<td>Browne et al, 1984</td>
</tr>
</tbody>
</table>

Figure 4.14: Flexibility terms found in literature structured schematically according to their focus in the assembly system life-phase. Originally put together by Johansson (2002).

In figure 4.14, many types of flexibilities are mentioned, as well as their nature. Some of them are closely linked to the overall goal of system flexibility, for example capacity flexibility and expansion flexibility. Others are more related to technical solutions like change-over flexibility and machine flexibility, where the linkage to the overall flexibility is a bit harder to specify. Suggested measurements for flexibilities at machine level may be far from the suggested -the time to accomplish a change. As an example, the definition of process flexibility is used.

- Process flexibility: The ability to produce a given set of part types, possibly using different materials in different ways (Browne et al, 1984).
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The measurements for this flexibility type could involve geometrical parameters, number of product variants that should be possible to manufacture, number of materials etc. These are obviously important parameters. However, the ultimate goal with the manufacturing system regarding flexibility is to be able to change. Since the design process starts with the ultimate goal and then breaking it down into sub requirements to accomplish these goals, the definition and the use of the term flexibility is correct. The other parameters (for example, process flexibility) are means to meet the ultimate goal, hence being goals at another level, and could be measured and used as well. However, conclusions made earlier states that it is better to measure the goals than the means and that a method should be based on the goal and not specific improvement or implementation methods, providing arguments for using the initial flexibility goal as the base measurement to use. It is also easier to argue for using a specific system solution when it could be placed in reference to a specific flexibility goal. Just stating that a piece of machinery has an awesome level of process flexibility will be harder to motivate for a cost minded board of directions.

![Diagram](image)

*Figure 4.15: The initial flexibility goals give the types and levels of different system flexibilities needed including uncertainties.*

Given the nature of the proposed method package; going from initial requirements and resulting in a first manufacturing system structure makes the user start with initial values on for example, flexibility. Using the value of the initial goal as a base gives results in the form of needed types and levels of system flexibilities, but with uncertainties due to the nature of the methods used and a number of factors affecting manufacturing system performance.
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These uncertainties could be calculated or estimated (see figure 4.15), giving the lowest levels of flexibility allowed in the process.

One should note that a specific type of flexibility is not worth anything if it does not help to improve on the ultimate goal: to make money (Goldratt & Cox, 1986). This fact could also make flexibility a useless goal to strive for, if it is not needed to make money, or is too expensive to accomplish. Hence, all goals have to be specified before working towards acquiring means for reaching them.

4.5 Concluding remarks about chapter 4 content

To conclude this chapter, a number of low-level concepts to be used when describing manufacturing system properties have been presented and argued for. The concepts form the base for numeric parameters to be used in manufacturing system design conducted in phase 2, but are at the same time, useful in phase 3 and even in phase 4, since they are general and understandable. Higher-level performance measurements used in operations, which is a part of phase 4, also uses the proposed concepts as components. Figure 4.16 shows an already designed manufacturing system. The basic concepts used in the design phase would have different uses, even after the completion of the system, showing the potential of this approach.
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Figure 4.16: Possible uses for collected data when being in the form of basic concepts and units.
Chapter 4

These kinds of parameters are the building blocks for virtually all performance measures available. Therefore the types of data would be useful in many different situations, both in the design method and later, the factory floor control method.

To increase the usability of the concepts, a methodological structure has to be added. To know how the desired system properties should be turned into system solution parameters, and later, specific solutions, there is a need for a structuring method, supporting the definitions made earlier. In chapter 5, such a method is described and argued for.
A manufacturing system description structure
Chapter 5

5.1 Background and description

The need for a structured method to design and also analyse and improve manufacturing systems has been identified earlier. A first part of such a method was presented in chapter 4, introducing measurable factors and measurements to use. In this chapter, a working structure is introduced. The structure provides means for:

- Describing a manufacturing system layout.
- Giving the properties of the intended manufacturing system.
- Giving a more concrete picture of the emerging manufacturing system.

It should also be possible to incorporate the structure in a software tool. The structure is basically a working description to use when working with manufacturing parameters.

The structure is formed after experiences made during the pre-study phases of the project. Two ways of working have been tested in the empirical data collecting work within the prestudy phases for this thesis (Karlsson & Strömberg, 1998; Karlsson, 1999; Karlsson, 2000a; Karlsson, 2000b; Karlsson, 2001). The names of the methods are not generally accepted but defined here. They are used here to specify two different ways of studying the manufacturing within a company.

**Product based research method.**
Practically this means studying the product structures and following the product in any direction, for example from the beginning of the production chain to the delivery to customer. The influences the processes have on the product are evaluated.

![Diagram of resulting structures from using a product based research method.](image)

*Figure 5.1: Resulting structures from using a product based research method.*
A manufacturing system description structure

**Process based research method.**

Here the processes are central and the products are considered to be the throughput. The processes are identified along each product flow and then, the influence of each process on the production, is evaluated. The process based research method is chosen for the proposed structure. It is explained in theory and as an example in the following two sub-chapters.

![Diagram](image)

*Figure 5.2: Resulting structures from using a process based research method.*

These two methods are very similar, the main difference being the view of affecting factors outside the product flow. The product flow is considered within both methods. There are however, some differences concerning the resulting data structure and more so, the way the methods are practically used. In the case of a product based research method, the resulting data structure will be a row with events along the line of flow.

As seen in the figures 5.1 and 5.2, the process based research method would result in a tree structure with a chosen base level which is divided into branches, consisting of the different sequence of processes, resulting in different products (more about this in the following example). The process based method results in a structure where the production flow is put in its context and the product based method results in a structure where it is not.

One could argue that a product-based method would be easier to understand since it use the product flow as a base. Since the process based method also takes the product flow into account, both in theory and when structuring the manufacturing, the manufacturing flow will be easy to follow here as well. In addition, one can easier see the relationship between the product flows since many processes are dependent on each other and different products
may pass through the same processes. The primary feature of a process-based way of thinking is that of the relation of the model to the actual manufacturing system. It can easily be coupled to a tool for obtaining the necessary data, like lead-times and resetting-times. In the presentation of AIP in chapter 3, it is stated that changeability of the manufacturing system layout is a desirable property. A model where the manufacturing processes forms the base is needed to be able to model the changes. Then, if one knows the lead-times, the setup-times etc for the new or changed process, the influence on all affected product flows could immediately be calculated. This is particularly important when the situation is one of constant changes, both within the product structure as well as within the production layout and machinery. The ability to rapidly analyse how changes are going to affect the manufacturing could be of utmost importance for many companies.

Process flow analysis is not a new way of working. It is described by Olhager (2000) as a method to document activities in detail, compactly and graphically, with the intention of creating understanding of the manufacturing processes. The goal is to clarify potential ways of improvement. To describe and analyse processes and operations, diagrams and pictures are often used.

The fundamental steps in a process flow analysis are (Olhager, 2000):
1. Identify and catagorise process activities.
2. Document the process entirety.
3. Analyse the process and identify possible improvements.
4. Recommend suitable process improvements.
5. Carry out improvements

The proposed method package fits into this description as a tool for use in the first three steps, in the manufacturing system design phase.

When having decided upon a modeling structure, the next step taken was to decide how the different parts in the structure should interact. Computer programming languages are used to model real phenomenon in a computer. They are used as a tool for accomplishing specified tasks. Constructed laws, principles, specified concepts, units etc are used. Object oriented programming (OOP) was developed to accurately describe real world situations more easily than possible with conventional programming languages, therefore being a very good example on an interesting approach for using in a method.
According to Pohl (1997), the term OOP refers to a collection of concepts, including:

- Simulating activity in the world.
- Having user-defined types.
- Hiding implementing details.

Figure 5.3: The principles of hiding details and only sharing data between two object units.

He also includes coding related properties not to be used here. The major point applied in the method package is to avoid unnecessary transfer of data. The hiding of implementation is also used. Complex calculations regarding a process are to be kept within the process itself. A ground for such a procedure is the use of standard basic concepts, presented in chapter 4. How this is done practically is explained in this chapter.

This structure works for example, for improving efficiencies by indicating where the efficiency should be improved. The structure also helps with the main question regarding effectiveness: are we conducting manufacturing the proper way? Since productivity is seen as a function of efficiency and effectiveness, the structure aims at improving the productivity of the manufacturing operation.

5.2 Theoretical definitions

The foundation of the proposed process based methodology is recursive thinking or recursion. Recursion is a fundamental concept in mathematics and computer science. The simple definition is that a recursive program is one that calls itself and a recursive function is one that is defined in terms of itself. A recursive program cannot call itself always, because it would never stop. Therefore, a termination condition when the program can cease to call itself is needed (Sedgewick, 1993). A recursive mathematical example:

\[ N! = N \cdot (N - 1)! \text{, for } N \geq 1 \text{ with } 0! = 1. \]
Practically, in computer programming, a recursive procedure is a set of instructions that is partly repeated until a condition (termination condition) has been met. When met, all the remaining instructions within the set will be executed as many times as the set of instructions has been repeated for the selected condition to be met. This could be illustrated as follows:

![Diagram of a recursive program](image)

**Figure 5.4: The working principle of a recursive program.**

[A] is a depiction of the process of repeating until one specific instruction, the termination condition, has been met. The remaining instructions within each set (square) will not be executed. When met (in A4), it stops calling itself and starts to behave like [B]. That is, it starts by executing the remaining instructions in B4, then the remaining ones in B3 etc.

The central point in this method is the process. The process is here measured and specified by:

- The input, like material and resources.
- The output, which is the product or partly manufactured product.
- The influence the process has on its environment

These factors are decided by the performance of the process itself. To be able to decide these three factors, one has to decide what to measure within the process and how to measure it. The total of the input, the output, the influence and the process itself is here called Functional Process Area (FPA). An FPA is depicted in figure 5.4.
A manufacturing system description structure

![Diagram of Functional Process Area](image)

*Figure 5.5: Functional Process Area.*

The production can be broken down stepwise into FPAs recursively, with the process as a recursive element. One starts at the highest level desired to be analysed, i.e. the factory. Then it is broken down into sub-FPAs, that in turn are broken down repeatedly.

![Diagram of An FPA shown as a set of FPAs](image)

*Figure 5.6: An FPA shown as a set of FPAs.*

Using the process as a recursive element means that the process is the object to identify. If the process can be divided into sub-processes, the FPA should be broken down into sub-FPAs. The termination condition is when the process consists of processes of low enough level, decided by the method user. It could be for example, individual operations. The result will be the FPAs, presented in a tree structure.
This picture shows an example of a tree. A tree is formed of nodes. A node in a tree, except for a special node called root, has one parent node and zero or more child nodes. The root node has no parent. A node that does not have any child nodes is called a leaf. A sub-tree of a node consists of that node and all its descendent nodes – its child nodes (Elmasri & Navathe, 1994). The tree in the picture consists of 3 levels. The highest level is the root node at level 0. The lowest level is the leaves which accordingly is level 2. Trees with two nodes are called binary trees and trees with more than two nodes are called general trees or forests. Figure 5.7 depicts a general tree.

In figure 5.7, A and B represents two chains of FPAs that form the lowest level within the factory. Each FPA in the lowest level consists of a row of individual operations. The elements in the row would be the sub-FPAs with pointers down to the next lower level. In the case of the lowest level, the array elements would be individual operations, or what has been decided by the method user, and no pointers downward would exist.

When that has been done, one starts analysing at the lowest level which is the FPAs that consists of individual operations. The analysis is being done with the help of a tool, where the areas that are included within the process are analysed upon how they affect certain factors that are important for the output and influence of the FPA. The tool is discussed later in section 5.3. When all FPAs on the highest level have been analysed, the input, output and influence are summarised in order to obtain the total, which is the input, output and influence on the next lower level. This is done repeatedly accord-
A manufacturing system description structure

ing to a suitable data structure method. Finally, the performance at the highest level is calculated. This could of course be done at a sub-level if desired.

Areas to consider when evaluating an FPA in this theory is structured after the division of research areas in chapter 3:

**Supply**, which is the area of supplying material and components to and within the process. It also involves the transportation of manufactured goods from the process. A large part of the area of logistics is covered here. This area resembles the area presented in chapter 3.3.2.

**Information** covers all information distribution from, within, in and out from the FPA. It includes Production Planning and Control (PPC) as well as Product Data Management (PDM). This area resembles the area presented in chapter 3.3.6.

**Human resources** covers organisational issues as well as educational and other personnel related questions. This area resembles the area presented in chapter 3.3.3.

**Manufacturing process** includes machine related issues like reliability, processing times, resettings etc. This area resembles the area presented in chapter 3.3.4.

**Product** is an area which includes product related issues like product design, choice of materials and such, that affects the output of an FPA. This area resembles the area presented in chapter 3.3.5.

Commonly, more than one area affect the performance. A complex product design could for example, cause the need for more resettings than another design would.

The influence the FPA has on its environment is roughly divided into:

**Flexibility.** Flexibility is defined earlier as changeability. It could for example be divided into the possibility to produce entirely new products, to manufacture different product variants and to be able to change capacity to meet changes in demand or any other definition closing in on technical flexibility factors. Flexibility should be considered both on a long-term basis as well as a short-term basis. The flexibility referred to here is the one of the entire FPA, affecting the environment. The flexibility of internal processes may affect the other influence factors as well.

**Speed.** Included here are for example lead-times. Everything that affects the speed and swiftness of the system should be included.
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Robustness. The reliability of the system when it comes to brakeage, downtimes, the amount of quality approved products manufactured etc. These are non-expected events that affect the manufacturing negatively.

Resources needed. The amount of resources needed to manufacture the products in the FPA. It could be measured in money, hours or anything appropriate.

These four areas should be divided into measurable factors for the general use within a factory. Factors were presented in detail in chapter 4. They are very wide in their definitions, which is the intent. Since the method is to be general in its nature, it could be unfortunate to define them harder because of the risk of making the method unsuitable. Defining them harder is left to the users.

Also notable is that the measurable terms presented in section 4.6 are not specific to any of the influence types. They could be used for analysing any of the influence factors. This goes especially for robustness and resources needed.

To make combining of factors and manufacturing areas a bit more intuitive, a working method should be used. In the pre-study phase, the factors were arranged in the form of a matrix, but it could be done in any suitable way.

5.3 Combining factors and areas

The matrix form was suggested by the AIP project group, as a form of helping to decide relationships between different performance deciding factors and the different manufacturing areas (AIP project group, 2001). It has however, not been tested. There could be better ways of accomplishing this. The matrix form does perform the task of presenting and explaining how the process of mapping manufacturing areas to performing deciding factors should be conducted.
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### Manufacturing areas

<table>
<thead>
<tr>
<th>Influences on manufacturing systems</th>
<th>Supply</th>
<th>Information</th>
<th>Human resources</th>
<th>Process</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup time (New system)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rebuilding time (Old system rebuilt)</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Resetting time (Product variants)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of resettings</td>
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<tr>
<td>Que time</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Processing time</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Throughput time</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Number of operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand-still</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Error frequency</td>
<td></td>
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<td></td>
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<tr>
<td>Materials transfer</td>
<td></td>
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<tr>
<td>Materials handling</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*Figure 5.8: An evaluation matrix used for deciding the relations between different performance deciding factors and the different manufacturing areas (AIP project group, 2001).*

The column headings are the manufacturing areas and the row headings are performance-deciding factors. The factors are identified earlier as being important (see chapter 3), but are not stated to be the only or most important factors. Rows could be added or subtracted and the headings could be changed if other factors are found to be important. They are however, functions of the basic measurable terms, presented in section 4.4, which are used as the final design elements.
Chapter 5

The main use of the matrix is to answer questions of the nature: how does a specific manufacturing area affect the factors identified, of this FPA? Also, for each case (in each square within the matrix) one or more problem solving method and measuring method could be assigned. This makes the method expanding into development phase 3. Therefore, the testing as well as assigning of problem solving and measuring methods is outside the scope of this thesis.

Having defined concepts and units, the FPA structure and the combination matrix give:

- A tool for structuring basic requirements for a manufacturing system.
- A tool for mapping requirements in different manufacturing areas to use as a help when deciding each FPA’s influence on the rest of the manufacturing system.
- The possibility to break system performance measurements down into basic measurable terms.

To explain how all the presented theory is to be used, a very simple example is provided in the next section.

5.4 An example using the FPA definition

As an example, designing a fictitious factory, that shall manufacture radio controlled model boats, will be used. The product is divided into three totally different product families.

- Sailing boats without engines. Two different hulls but the electronics inside are the same. The mechatronic equipment differs a little since different sail sizes require different moments of inertia on sail handling equipment.
- Engine powered racing boats. The propulsion could be electrical as well as combustion. Different electronic and mechatronic components as well as two different hulls.
- Electrically powered military vessels, which are more or less hand made custom jobs.

The electronic and mechatronic component are to be considered standard components. These are components such as servos, speed regulators and batteries. They are bought from different sub-contractors. Most of such
A manufacturing system description structure

components can be used in all three product-families. What differs is the combination of the components.

Hulls are to be made from two different materials. Fibre reinforced epoxy and injection-molded ABS plastic. The fibre-reinforced hulls will be bought from a vendor but the ABS-hulls will be made in house. The ABS process has a relatively long resetting time and the tools are considered expensive. These are the only things known, when starting the examination of the manufacturing system design. At first the only FPA that is known is:

![Diagram of the factory as the first FPA.](image)

*Figure 5.9: The factory as the first FPA.*

Then the production is divided into FPAs. The first three areas recognised are the three main product flows.

![Diagram of the factory FPA, broken down into three FPAs that are the main product groups.](image)

*Figure 5.10: The factory FPA, broken down into three FPAs that are the main product groups.*
Chapter 5

The three product flows are then divided into FPAs as well. To keep the example simple, just one flow will be illustrated from now, in this case flow no 2, motorboats. This should not result in any simplifications that make the process of breaking the production into FPAs easier. The simplification is made to be able to illustrate the process. Without the simplification, the resulting structure would be too large to print.

Again, the central areas are the processes within the FPA. Everything else will be regarded as input, output or influence.

Figure 5.11: Product flow 2, broken down into FPAs.

One should actually build a chain of FPAs for each of the two ways of obtaining a hull and the purchase of electronics should be put in parallel. The problem of depicting parallel flows is discussed later in chapter 6.

To continue the example, the painting process is selected. After having decided what processes are needed, the flow can be divided into FPAs accordingly:
A manufacturing system description structure

Unpainted assembled boat

Cleaning  Masking  Painting  Drying

Applying sticker: Visual check

Painted assembled boat

Figure 5.12: The FPA describing the painting process, broken down into FPAs consisting of individual operations.

The process of manufacturing radio controlled model boats has now been broken down according to the theory of functional process areas. That is, each FPA now consists of individual operations only, which is decided to be the termination condition. This should be done for each FPA, originating from the base one, which in this case is the factory.

The resulting structure is then presented as a tree structure. The tree depicting the entire example factory breakdown will however be quite excessive in size and even more so if the production situation evaluated is larger than this. Therefore only one branch of the tree is displayed here.
Chapter 5

Figure 5.13: The FPAs, arranged in a general tree structure.

At this time, when the relations between processes have been charted, one uses the evaluation matrix as a help to evaluate how the important factors affect this, the lowest level chain of FPAs. Thereafter, one examines how the results from this chain affect the painting process. The chains from the other processes shown in figure 5.11, are examined how they affect their particular chain. Since the same has been done with flow 1 and flow 3 in figure 5.10, the three measurements from the three FPAs there displayed, can be summed into a final result for the starting, highest level FPA (fig 5.9), which is the factory.

The individual operations, now displayed at the lowest level in the tree, can now be evaluated by using the evaluation matrix shown in figure 5.14, deciding the level of the influence factors.
A manufacturing system description structure

Manufacturing areas

<table>
<thead>
<tr>
<th>Influences on manufacturing systems</th>
<th>Supply</th>
<th>Information</th>
<th>Human resources</th>
<th>Process</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup time (New system)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rebuilding time (Old system rebuilt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resetting time (Product variants)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of resettings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Que time</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Processing time</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Throughput time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand-still</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials transfer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials handling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.14: The use of the evaluation matrix.

In the case shown in figure 5.14, one is examining how the human resources within the FPA, affect the queue time that FPA. Within the square, there should be descriptions of methods available to measure the sought after information, as well as proposed methods on how to improve performance in this field. This should be done for all five fields on the x-axis and all possible ways of influencing the manufacturing, presented on the y-axis. In this way, no factor should be overlooked by anyone.
Chapter 5

Transforming the factors into the basic concepts (presented in section 4.6.1) makes the factors expressible as general performance measurements, useful at different levels in the FPA hierarchy. As stated in chapter 4, the concepts should be combinable into higher-level performance measures (see section 4.2.2 and 4.4.1 if necessary). This simplifies the understanding of what for example, the setup-times, amount of operations or number of resettings at the lowest level, mean for the highest level in the hierarchy.

![Tree diagram](image)

Figure 5.15: The summarisation of all FPAs up to factory, starting from the lowest level.

When evaluated, the influence each FPA has on its environment is put together, all the way up to factory level. In practice this would mean mathematical treatment (possibly adding or multiplying) of the basic factors from lower levels up to the top level. From there, the calculated factors may be used for calculating higher level performance measures, for example those mentioned by Slack et al (2001), presented in section 4.3.2.
A manufacturing system description structure
Chapter 5
The resulting manufacturing system design method
In this chapter, the components presented in chapter 4 and 5 are put together and explained. The results are also critically reviewed and further research is suggested.

6.1 Method work flow

The most important issue to remember about this method is the general working principles and components, being the use of general and simple factors to describe manufacturing system properties and the simple structuring of the manufacturing into flows.

In addition to the example in the previous chapter, a short method description is made to clarify the use of the method:

1. Based on the requirements specified in phase 1 (see figure 4.1), the manufacturing requirements are stepwise broken down into requirements put on lower level units like departments, groups etc. This is done until one reaches a set of operations, performed by individual machines or humans, which is the termination condition of the break down process. When this is done, the structure of the manufacturing has been decided. At each level, the initial requirements are also broken down into requirements that have to be put on the next lower level, to accomplish the performance needed.

2. When having reached the lowest level, one evaluates the performance of the lowest level set of operations by using measurable characteristics identified as being important. The characteristics are expressed in the basic performance measures in the form of concepts, presented earlier in chapter 4.

3. After having conducted step 2, there is the possibility to attach real manufacturing solutions to each FPA, being FAM-cells, NC machinery, manual workplaces etc, depending on the performance needed. The performance values of these solutions are expressed using the same concepts as used in the breakdown process. They are then added up and one looks at the influence the evaluated set has on the next level going upwards. This gives the partial performance needs for that level.

4. This process continues until one reaches the desired level, which at most can be the level used as a start in step 1.

5. Then one has to review the highest-level performance, to see if the total performance matches the performance needed according to the initial requirements.
The resulting manufacturing system design method

The total behaviour of the factory, expressed in basic performance measures may be used for calculating higher level performance measures.

The behaviour of the three individual departments, giving the behaviour of the factory, presented in the specified concept.

The behaviour of the four individual processes, giving the behaviour of dept. number 2 presented in the specified concept.

Some possible measurements:
- Total throughput time of the painting process
- The flexibility of the painting process
- Idle time
- Capacity available
- Waste due to behaviour of individual operations
- Possible fluctuations in capacity.

All of them, expressed in basic performance measurements / concepts.

Figure 6.1: The use of basic concepts (see chapter 4) through the tree structure.

As shown in figure 6.1, the process is rather simple to conduct. One problem could be that such a tree would expand into something that is rather cumbersome to draw and follow. It could be feasible to draw only a part of the intended manufacturing system. One has to be careful not to miss out something just because it is excluded and therefore not drawn in the tree structure.

To decide the needed performance parameter values, the concepts introduced in chapter 4 are used. Presenting the role of the concepts a bit more in detail than above, values on flexibility, capacity, volumes, lead-times etc (see section 4.4.1) are calculated for the FPA at the highest level, originating
from higher-level performance measures and corporate goals (see section 4.2.2). These parameters are then used for deciding the performance needed at the next lower level where the performance of each FPA is decided. The procedure is repeated for the next lower level until the lowest level is reached.

The performance evaluation at each level is conducted by using an appropriate approach like the suggested matrix (see section 5.3). The matrix provides an aid deciding what system solution properties could affect the performance of the solution. By changing performance-deciding factors in the matrix row headings, it could be used at different levels in the FPA tree hierarchy. The performance deciding factors should then be broken down into the concepts presented in chapter 4, giving general performance measures, useful at different levels in the tree hierarchy and in the company.

It is likely that the chosen solutions have performance figures that differ from the original performance measures needed. This is due to solutions having different values on capacities, flexibilities etc, than is actually needed. When the solutions have been chosen, the method is used upwards in a recursive fashion. The partial performance numbers are put together, giving the total performance of the related higher level FPA (see figure 6.1), until the highest level FPA has been reached. Then the total performance is compared to initial performance goals and requirements.

If the performance is less than needed, make appropriate changes in the given FPA structure or do it all over again. If the performance is acceptable, one has a model of a manufacturing system that could be improved further by using other more specialised methods, hence leaving phase 2 for additional improvement in phase 3.

6.2 Discussing the resulting method

The material presented in chapter 4, 5 and 6 leaves some questions to be answered. There are for example, different methods available that may be used instead of suggested approaches or questions regarding the use of the method.
6.2.1 Using an alternative manufacturing description method

Inventing and developing a new type of description system, the FPA system, may be arguably unnecessary since there are other description methods available. One of the most well known is the IDEF type of graphical description. IDEF 0 is a de-facto standard for process modelling, using a hierarchical top-down structured representation of a subject (IDEFine, 2002). The IDEF 0 structure could be used in this method. There are reasons for not just merely using it. The FPA describes exactly the ideas behind the developed method. Using IDEF 0, would make it necessary to adapt the method or re-define certain parts of it, with the possibility of removing the focus from one main part of the presented method package: using general basic performance measurements and using them through the process hierarchy. Learning the idea of FPAs is not considered to be a large burden for someone with knowledge in IDEF methodology. Neither would it be hard to learn for someone without such knowledge. There are therefore no or few reasons for not using FPAs instead of IDEF 0.

6.2.2 Degree of orthodoxy needed when using the method

A most inevitable question is how strictly one does have to use the method, leaving further questions about if every suggested piece of action have to be conducted or is the general structure the only thing that has to be followed. To answer the questions, one has to recall that the structure using suggested concepts should give the users a mean:

- To create an understanding of the arrangement of the manufacturing.
- To show how different areas interact and affect each other.
- To help to evaluate the performance of each stage in the production.
- To suggest improvement methods by using an appropriate tool, i.e. the evaluation matrix.

This was the intention with designing the method as presented. At this stage, the questions are impossible to answer with accuracy because of the lack of testing of the method on practical cases. Some variations may be allowed as long as it provides such means.
Chapter 6

The most important aspect of the method is the use of general concepts, describing manufacturing system solution properties. This is the core of the method, basically defining the method and making it different from others. The other central part of the method is the structuring of the manufacturing system for revealing the relationship between the manufacturing processes. Using the proposed FPA structure could do this, but other methods could be used as well. The IDEF 0 is one possibility; hence using other methods in this function is a possibility that may not affect the resulting design negatively. Though, this is yet to be proven.

The use of the different concepts is important to the method. However, additional concepts not suggested in this thesis could be used. They should follow the guidelines of how to select design concepts (section 4.3). It is even recommended for the user to review the suggested concepts and compare them to the company specific higher-level performance measures to see to it that the method supports them. This is an intended property of the method; to be customisable to fit different user requirements.

6.3 Method development

The method is on a design stage and has to be developed and evaluated further. The division into FPAs and the structuring into trees should be tested and reviewed as well as the performance evaluation in its present matrix form. To create or choose algorithms for searching and operating on the tree as a data structure is outside the scope of this thesis, but is still an important task for future research. Algorithms for such operations are well known and are available in literature covering applied computer science, possibly making the task quick to complete.

Another issue concerning the tree structure that has to be decided upon is how to proceed when having parallel or shared processes, both situations being common in a factory. This will be an issue, especially when drawing a tree structure. During the research phase, when the tree structure was first introduced and also used as a part of conducting case studies, different variants were tested. None were actually seen as being superior to the other. A shared process has been depicted at different locations in a tree but has been labelled parallel and the capacity has been reduced to what could be expected needed for completing each manufactured product type. Parallel
The resulting manufacturing system design method processes were more difficult to depict in an easy way. The first version used is done by depicting parallel operations as a single FPA, which in turn is broken down into each operation.

![Diagram showing parallel processes]

*Figure 6.2: One way of depicting parallel processes, though breaking the rules of the initial definitions made earlier.*

This kind of depicting does not conform to the initial definition made in chapter 5 since parallel processes are depicted as being in series.

The other version is to depict the parallel processes into a single set, showing explicitly that these are parallel processes.
Chapter 6

Figure 6.3: Another way of depicting parallel operations in an FPA tree structure.

This version does conform to the specifications presented in chapter 5.

Deciding which version to use has to be specified, which is a part of the practical test of the method, hence being future research.

Since the intended use includes comparing desired manufacturing system properties to properties of possible solutions, research covering such solutions has to be conducted. Decisions on how to label and measure system solution properties have to be taken. This research has to be carried out in a more extensive fashion than just including it in the field-testing of the structure and suggested concepts.

A desired approach would be to form a method for deciding manufacturing system properties. In this way, every solution available would be parameterised according to the same standards.

The research would then include the deciding of concepts that are appropriate for system solution evaluation.
The resulting manufacturing system design method

Figure 6.4: Standardised concepts used for providing a link between the desired properties of the manufacturing system being designed and the properties of the available solutions.

The concepts suggested in chapter 4 are aimed at being appropriate for such use, in addition to deciding the manufacturing system performance. If, however, there are other concepts found to be appropriate for use when comparing properties, it is likely that they are functions of the concepts introduced in section 4.4.1 since they are low level standard parts of many performance measures, which makes the research presented in chapter 4 valid still.

A conclusion is that there is a lot of research and testing to be conducted before the suggested design method structure becomes a complete method. Most of the work would be field-testing and sorting out deficiencies. The exception is the research that has to be conducted focusing on describing manufacturing system solutions as general concepts.
Results part 3

Manufacturing control system
Developing a manufacturing control system
Chapter 7

In this chapter, a suggested manufacturing control system design is presented. The intention is to develop a control system that independently from the factory layout can provide the positive effects associated with Just In Time related control methods like Kanban, but at the same time, retain a larger degree of flexibility than normally possible with such methods. Notable is that the suggested solution is not a new control method; it is a technical system for implementation of different control methods in a way that the method most suitable at the moment, may be chosen. The control system design is intended to provide flexibility and usability to cope with different changes in the manufacturing situation, originally induced by the market. Examples of changes are the introduction of new products and new product variants, shifting production volumes, changes in the factory layout, introducing new manufacturing processes and the removal of obsolete ones.

7.1 Introducing production planning and control

Controlling the factory-floor manufacturing situation is often recognised as an important activity for achieving high performance manufacturing. Manufacturing control (MC) is a topic, highly related to modern manufacturing strategies and philosophies. Discussions on Just In Time often include the Kanban and Conwip MC methods, where Material Requirements Planning (MRP) based methods many times are mentioned in negative terms. It is clear that MC does influence the performance of the manufacturing system as a whole. The demands put on MC methods have varied in conjunction with variations in demands put on manufacturing systems as well. Goals for Just In Time followers are for example low inventory levels and short lead-times. This reflects on JIT-related methods, e.g. Kanban, which often are used for accomplishing these goals.

An overall performance factor that has become more important is flexibility, therefore being an important property of manufacturing operations as well. Using the Kanban method in an environment characterised by changes of different kinds, is known to be problematic (Olhager & Rapp, 1985). There are several ways of coping with these problems, one of them being not to use Kanban at all, which could be one reason for MRP being so popular. MRP is able to handle changes of different kinds more effectively, but is not as efficient on keeping inventories down or supporting short lead-times (Plenert, 1999a).
Developing a manufacturing control system

The strengths and weaknesses of the different types of MC methods make them highly related to what kind of factory floor layout is used. The lack of flexibility in terms of for example, manufactured product volumes, makes the Kanban method rather unsuitable for use in a department layout, but suitable when controlling a structured flow like a line (Karmarkar, 1989). Demands put on manufacturing companies to be flexible in the sense of quickly introducing new products, new product variants and shifting volumes may force a changing of manufacturing flows and even layouts through a factory (Onori & Alsterman, 2000). This would undoubtedly cause problems in the manufacturing control function.

Recapitulating what was found out in the earlier pre-studies, presented in chapter 3, Production Planning and Control (PPC) related problems identified were (Karlsson, 2001):

- Little or no control over the actual situation.
- Lead times, given by the PPC system, were often inaccurate.
- PPC systems are not designed for the given type of manufacturing or the manufacturing strategy chosen by the company.
- Unfriendly user interface of PPC software.
- The actual material flow does not comply with the model in the system.
- Poor or non-existing handling of rush orders.
- The system is often considered a burden rather than a helpful tool.

The software PPC systems were all MRP based, with similar functionalities but implemented by different vendors.
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Figure 7.1: The use of MRP based PPC systems at the studied companies (Karlsson et al, 2002).

No dedicated MC systems were used by these companies for control inside the factory. Kanban systems were in some cases used for controlling material flows between plants or between vendor and the studied companies, which is another type of functionality, not handled by the MC system.
Developing a manufacturing control system

7.2 System goals and conducted research

The research is aimed at developing a system for controlling the materials flow on the factory floor and activities included in the manufacturing operations, vital to the manufacturing of the products. The design and use of PPC systems in highly changeable environments was covered in a pre-study, the main focus being the MC function. The pre-study, a more focused literature review covering the topic area, as well as focused studies at selected plants resulted in general goals with the factory floor control system. The focused studies were first presented in Karlsson & Halonen (2002). This set of goals is the partial goal E, depicted in figure 1.2 in section 1.2.

The goal with this research is to develop a structured manufacturing control system concept, with main properties being flexibility in the sense of reconfiguration and use, as well as real-time data distribution and acquisition for use on the factory floor. Main properties to build into the system are:

- Adaptability: It has to be adaptable to changes in layouts, production volumes, and changes in the product structures.
- Low cost: it has to be cheap to buy, implement and use.
- To fit into an already existing PPC environment: When asking subjects for desired characteristics of a control system, many requested that investments already made should not be made obsolete. This demand has been extended into that it should fit different scheduling environments.
- To provide relevant and accurate data.
- To be simple to use for operators and management alike.

Also notable in the pre-studies were differences in opinion, depending on where in the hierarchy the interviewed persons were placed. People situated outside the factory had requests for additional functionality such as being able to keep track of company related activities more accurately. Linking shop floor related activities to higher-level performance measurements was expressed as being desirable. One could argue that such functionality is included in Enterprise Resource Planning (ERP) systems, in some cases already in use by the company. But there was often a specific demand for making it possible to monitor the current status of the manufacturing more accurately in order to be able to aim for company specific performance
Chapter 7

measurements and to react on events quicker than possible at the time of study.

Workers on the factory floor were interested in the possibility of being able to see the status of operations on which their own work was depending, helping them to focus on necessary tasks in time.

To accomplish a system, carrying these properties, the research has been divided into different parts, related to both information handling and MC method specific aspects. The intended use of the suggested solution is for providing the control function. Planning and scheduling is still to be conducted by using other types of systems.

When discussing manufacturing control issues in this chapter, department type layouts are often used in examples etc. The reason for this is that they in many scenes are worst-case scenarios when it comes to manufacturing control. If the control function could be carried out in such a situation, it is possible to carry it out in factories with different layouts.

7.3 Conducted research

The research was divided into different parts. General PPC research was conducted as surveys and case studies as a part of a larger project, over a period of three years, at 10 manufacturing plants in Sweden. The results from these studies are described in chapter 3. All plants were using MRP based schedules as manufacturing control. Hence, no factory floor control systems were utilised. Therefore, such methods (for example Kanban) were studied only in theory. Emphasis was put on finding articles describing cases were different current factory floor system installations and uses were evaluated.

High-speed information handling and retrieval is a key issue when applying factory floor control, especially when providing accurate and relevant data to people needing it (Gumaer, 1996). Studies focused on information handling and retrieval were made at the Posten AB (Swedish Postal Services) Gothenburg terminal and three printing plants, specialised in newspaper printing. The reasons for choosing these four companies were primarily for the nature of their operations and their need for accurate manufacturing related information. The time from the obtaining of the product specification to the completion of a batch, is a couple of hours for newspaper printing as well as for Posten AB. Posten also has to be able to track product identities
Developing a manufacturing control system

through the flow (i.e. e letters, parcels etc), basically in real-time. Such conditions make these companies valid study objects. These studies, conducted as interviews and studies at the sites, were focused on establishing what types of data are retrieved and used, how the data is retrieved and handled and the type and magnitude of associated problems. The studies were also intended to give ideas for the structure of possible end solutions.

To be able to create a control method that has the desired effects on the manufacturing, a review of currently available scheduling and control methods was necessary, finding key elements or rules in the methods. Information on the structure of the methods and what properties causing positive and/or negative effects respectively was searched. The structure of Kanban, CONstant Work In Process (CONWIP), Theory of Constraints (TOC) and its relative Optimised Production Technology (OPT), Bottleneck Allocation Methodology (BAM) and the MRP principle were selected. MRP and BAM are scheduling and/or planning systems but are often also used in the control function. The scheduling methods have been studied in order to know what information is needed when making schedules as well as the nature of that information. The research goal of making the suggested system usable together with software already in use makes them valid as study objects as well.

Kanban and CONWIP are here classified as control systems, traditionally used on the factory floor. Different uses in for example, external order-delivery systems are also available. OPT/TOC are used for controlling the workload by finding a system bottleneck and could therefore be seen as a control system or a system used for helping out the planning/scheduling function. Control methods have been studied in order to know what kind of rules to incorporate in the control part of the developed MC system.

In short, the reviewing of scheduling and control methods was conducted for two reasons:

- To find the different types of control rules and give information on how to implement them in the design to be suggested.
  - By studying systems in theory
- To find what is important characteristics in MC methods and principles.
  - By studying systems in theory
  - By studying practical cases to see what is important in high-speed information handling and retrieval.
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7.3.1 The nature of a factory floor MC system

MC systems are here defined as being information distributing systems that applies specified rules and conditions, at specifically chosen moments at specifically chosen locations in order to accomplish manufacturing control. Hence, the basic building blocks of MC systems are:

- An information distribution system
- Applied rules and conditions
- Applied timing

In addition to information distribution, MC systems applies rules and conditions, intended and designed for controlling different manufacturing parameters. These rules tell the user for example, when to start manufacturing of a certain part, when to refill material buffers, how much to manufacture and when the manufacturing should be finished.

Timing basically refers to the ability of conducting the control tasks at the right time. Rules and conditions very much specifies when an activity should take place, making the timing dependent on the rule design. It is also dependent on receiving accurate and valid information from the manufacturing system.

Basic information on information system design should therefore be applicable in an MC system. An obvious statement to make is that information should be accurate, valid and available. These demands put on an information system has to be fulfilled by an MC system as well to be able to comply with performance demands put on the manufacturing system.

Hence, the process of designing an MC system is of a multifaceted nature, including information distribution and rule design. The similarity between the manufacturing system organisation and the control method has to be recognised as well as the demands put on the manufacturing system as a whole.

7.3.2 Information distribution issues

Mapping information flows in an existing factory, there are often numerous different paths and means for information to reach its destination. Information, vital to the performance of the controlling of manufacturing, many
Developing a manufacturing control system

times has to pass vertically through an organisation hierarchy. The information has to reach people having knowledge about the information content and having authority to take action according to the information content. Forza and Salvador (2001) states that ensuring control upwards and downwards through hierarchy leads to some drawbacks:

- The continuous flow of problem related information tends to overload managers and therefore increasing the risk for important information to be overlooked.
- The long control loop from operator to manager is not timely, leading to poor and lengthy process control.
- The described communication pattern ignores process-related information retained by workers, thus losing the benefit of an important resource.

They also state that information flows that support the control of the transformation process in high performance manufacturing can be characterised as:

- More timely information pointing out control problems in the plant is conveyed by means of horizontal information flows, taking place between workers and by means of external information flows conveying customer feedback or non-conformities.
- More intensive bi-directional communication on their process capability and feedback on nonconformities.
- A smaller amount of control-related information goes upwards to supervisors and managers, conveying only problems that cannot be tackled at lower hierarchical levels, reporting exceptions, and tracking the main process performance indexes, both cost and non-cost.
- All-channel (both horizontal and vertical) communication is enabled by visual control systems, which are displayed at appropriate locations that indicate overall performance.

Information collected by the operators lead to short feedback loops and therefore gives possibilities for quick response when unexpected situations occur (Forza and Salvador, 2001).

This could be seen as a constraint for a manufacturing company since not everyone is able to accomplish strong horizontal information flows. The main reason being the correlation between factory floor layout and the control information flow, often being highly structured after the nature of the manufacturing system layout and organisation. In a factory organised as
manufacturing cells or lines, the possibilities for horizontal information distribution would be augmented since the different stations forming the information flow is closer together and formed according to the manufacturing flow. The almost opposite being a department layout where different manufacturing stations could be located far from each other and at seemingly random locations. This argumentation is supported by research showing strengths and weaknesses of certain factory floor control systems (Karmarkar, 1989; Suri, 1998).

Two factors are therefore identified as being important success factors for MC information system development:

- Enhancing the possibilities to communicate vertically in a hierarchy, providing only accurate and relevant information to supervisors and management.

- To provide means for horizontal information flows regardless of factory floor layout.

When studying information and MC issues in the pre-study phase (chapter 3; Karlsson, 2001), the importance of informal information paths was discovered at the studied companies. Informal systems consist of everything that is not a part of the dedicated PPC system or method. It could be operators discussing MC issues in order to control the manufacturing. It could also be a planner doing non-specified tasks in order to make the manufacturing run smoothly. In some cases a planner is vital for the function of the plant (Cammarano, 1997).
Such informal systems have to be taken into account when designing a control method. A problem is that they may be functioning differently in different companies or even in different departments within a plant. A found commonality between the studied companies was that the planners or a person with similar tasks had an overview of the situation at the plant in order to make operations run as smooth as possible. Another commonality was the need for operators to speak to other operators, even in other depart-
ments, to get a personal overview of the situation. The overview of the situation usually consisted of knowledge about the whereabouts of different orders and products as well as the current and future capacity situation of connecting processes that may affect or be affected by the asking operator.

7.4 Finding control system fundamentals

To be able to design a first control system draft, the Posten Gothenburg terminal and the three newspaper printing plants were studied as a complement to the other more general material collected. The intention was to find how these companies had solved similar problems as the ones specified in the problem definition, especially real-time information handling and retrieval. The nature of their operations was also studied in order to be able to map their solutions to their operations related problems.

7.4.1 Newspaper printing plant studies

Newspaper printing is very dependent on short and accurate lead-times. Some of the processes are sensitive to disruptions, making the need for monitoring imminent. The status of the printing plant is therefore monitored in different ways, in many cases retrieving data in real-time. At the studied printing plants, information is handled in different ways. First of all, the plants are divided into two main functional areas, the printing process in itself and the mailroom where the printed newspapers are handled and packaged. In the mailroom, the work is often dependent on manual operations.

![Diagram of newspaper production process](image)

Fig 7.3: The newspaper production process divided into two stages and six sub processes (Nordqvist, 1996)
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In general, different kinds of data are directly available from the equipment in the printing process. The mailroom works differently, where a considerable amount of information handling is carried out manually, making the information handling different in nature.

The product specifications are received from the customers by computer communication on a day-to-day basis. Since the order frequency and the sizes of the production runs are known in advance, the work is already scheduled before receiving the product specification. The schedules are planned tightly, not leaving room for time lost to disturbances. The planned slot for a production run could be 45 minutes to somewhere around 2 hours. Even small disturbances may result in down times that are as large as the planned production slot itself. There is a need to be able to get an instant picture of the situation in the production due to occurring late changes in the product specification made by customers.

The printing process

The printing process is heavily automated, mainly consisting of printing presses. There are many key elements that are connected to sensors, dye levels, temperatures and other printing quality affecting parameters. There are also machine related sensors, measuring parameters related to machine safety and such.

Figure 7.4: Four-high units (compact design) and arch-type printing units in newspaper printing (Kipphan, 2001; © Prof. Dr H Kipphan, used with permission).
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Figure 7.4 shows a web-fed newspaper printing system suitable for a confined space. This setup is very compact. The studied printing plants had different printing machines, being four or five stories high, but the working principle of the system shown in the figure is similar.

At the studied plants, most of the desired information is available from the press system. At one plant, the remaining types of wanted information will be available in a short period of time through technical modification of the system. Measures available from a printing press are for example (Clason, 2002):

- Availability in the form of production time used / total production time
- Hourly production volume
- Starting accuracy in the form of minutes late or early
- Stopping accuracy in the form of minutes late or early

Due to the nature of the printing process, there is a category of stops, originating from for example the paper or the ink that will occur no matter what precautions has been taken. Error analysis groups consisting of technicians take care and analyses the problems in the press when it is possible to detect a certain type of often occurring error. A specialist group could then be put together to solve the problem. At one site there is a maintenance system available, making it possible to follow up the activities maintenance department. The main interest seems not to be registering down times, but to classify and abolish stops. The main reason for this is that there are no new kinds of stops occurring and the approximate down times are known for each stop type. At one site, there is a internal comments paper circulating to the different departments, providing information on the functionality of the printing plant.

The mailroom

The mailroom is where the newspapers are handled and packaged. Certain operations are carried out, like inserting supplements, palletising, stacking and addressing. The work is often dependent on manual operations even though a lot is automated. There are for example, different kinds of machinery available for the insertion process, which though is an error prone process.
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Figure 7.5: Outline plan of an installation for finishing mass-circulation magazines (Kipphan, 2001; © Prof. Dr H Kipphan, used with permission).
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An example of a mailroom is seen in the figure above, where the printed papers comes from the pressroom (printing) and follows different flows, depending on the operations needed.

In the newspaper handling and packaging processes, many operations are manual processes or non-reporting machinery. Hence, large parts of the status reports are written manually, causing a unique set of problems; a lot is depending on the operator’s ability to use the reporting systems. There are different counters available though, that register the number of printed copies, the number of destroyed copies and the time available (Denex, 2002). Generally, the automated processes are more and bettered monitored than manual processes.

The mailroom often has their own reports and data collection, which makes seamless distribution of data harder to accomplish.

**Issues general for the entire printing plant**

Different kinds of statistics are made, for example web break statistics. The departments make press and mailroom reports. Usually the departments have people responsible for put together reports, which then are presented to the production manager.

People are making different kinds of analysis from the paper reports, calculating the influence from strategic stop types. The reason for this is illustrated by a quotation of one of the interviewed supervisors “A small error one day can be a big error the other day”. The same supervisor also states that there is a wish to get rid of the paper reports and only rely on computerised information distribution and stage. As it is today, a lot of people receive the copies of each report. There are also meetings every 24 hours with the maintenance department, where all the production runs during the next 24 hours are discussed. A list including all jobs entered in the maintenance system is reviewed in the morning and the made adjusted are noted.

Data systems implemented at the different plants vary somewhat in capability and price but the functions are similar. Generally there is a scheduling system, a system that communicates with the printing presses and there is some sort of general system, containing data not available from the other systems, for example maintenance data and production reports. The systems are often connected to each other.
7.4.2 Study at the Posten AB Gothenburg terminal

Most of what is said about newspaper printing is valid also at Posten. There are some differences however. The processes at Posten are mostly sorting processes and transportation. The way through the plant differs depending on the type of letter and if the mail already has been sorted in advance. Some processes are sensitive to disturbances and since the rate of flow often is very high measured in letters per minute, a stop may have large implications.

To be able to meet firm and close deadlines, the processes are carried out in high speed.

Destroyed products are not nearly as numerous at Posten as it is in newspaper printing, due to differences in the processes. At Posten, it is very important not to cause damage to the products. The obvious reason that every item of mail is unique and has a unique recipient.

Along the production flow, there are different automatic counters, keeping track on sent volumes. There are also mail readers/scanners that register address data, which is used by sorting mechanisms to send the item of mail to the correct destination. Data is retrieved and stored more frequently than every tenth minute. The data is used for e.g. showing strategic performance measures, to monitor the day-to-day production and to indicate disturbances in the production processes. Disturbance detection is though mostly done by the workers at the floor, since the layout and the nature of the processes often makes disturbances instantly noticed.

Communication problems of the type present at the printing plants due to the division into two different functional departments do not exist at the Posten plant. This is mainly due to necessary information being available at the different processes. The instant problem detection also helps when having to meet the strict deadlines. All in all, the supervisors had a good view on the status of the production at the Posten plant.

7.4.3 Final comments on the studied objects

There are a few things concerning these studies that should be kept in mind when reading about the suggested system solution.

The first issue is of a research technical nature. The products handled and manufactured by the printing plants and Posten do not change much over
time. Therefore it is highly questionable if they could be classified as being changeable environments, which is the working situation for the developed control system. The main idea with studying these companies was never to study such an environment, but to study more ideal situations where certain variables would be less affecting to the results. This would give information on how manufacturing control is implemented and how it works in an environment with less factors obstructing the carrying out of the control function.

The second issue is an observation made during the study period. Companies that monitors lead-times in the manufacturing continuously and accurately (i.e. the newspaper printers and Posten), do have well working scheduling systems. The main reason is identified as the constant feed of information about the times taken to complete an order. This is a central part of the suggested control system approach.

7.5 The proposed system design

The suggested system solution is a standalone computerised customisable control system, not directly connected to the higher-level PPC environment, but distributing information freely to wherever it is needed.
The order to start the manufacturing of a specific product is in the depicted case above, given by an MRP based PPC system which is a module in a larger ERP system. When the manufactured products are finished and ready to ship, it is reported back to the PPC system. The proposed control system consists of a database as a main part of an information distribution system. Strategic data is retrieved and distributed quickly by allowing downloading and writing to the database. In this case, sales and purchasing has access to the data as well as the personnel directly involved in the manufacturing.
Suppliers and distribution could have reading rights in order to better plan their operations to support the manufacturing or if they are given writing rights to the database, the manufacturing could be planned after the situation at the suppliers and distribution. Other corporate functions could be given access as well if desired.

Rules and conditions are then used in the applied control function, deciding when to perform an operation, the amount of work to be conducted etc. The proposed solution controls, as any other manufacturing control system, the manufacturing operations more in detail, than the general scheduling or PPC system does.

The suggested solution fits into an already existing PPC environment. It complies with the requirement to providing data for scheduling methods. It is also possible to incorporate well working MC methods by implementing their rules and conditions into the software.

If properly implemented into the software, the system should be able to:

- Use information based on time units from any scheduling method like Bottleneck Allocation Method (BAM) and MRP.
- Quickly find and provide data on constraints (bottlenecks), by using time, identity and location data.
- Provide relevant data by using real-time information retrieval and handling.
- Act as Kanban, CONWIP or any other control method, broken down into rules and conditions and entered into the system.
- Be modifiable in order to make vital information generally available that previously only was available through informal sources.
- Be modifiable to fit many known and used factory layout, department layouts and lines alike.

To be able to incorporate the advantages with informal information systems, the proposed computerised version has to be easily customisable in many different ways, making information vital to the smooth running of a factory available to different strategic functions within the company.

In order to be flexible, schedules should be revisable based upon unplanned events. To accomplish this, their process and data models, information systems, and communications structure must operate seamlessly in real time (Gumaer, 1996). Practically this means that actual lead-times in the plant has to be monitored, preferably constantly. This shows that one has to take into account the need for immediate and accurate status of strategic processes in
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the manufacturing plant.

All these demands do put some more specific needs on the detailed design of the system itself in the form of designing rules and conditions, deciding what kind of information should be handled by the system, real-time information handling and retrieval and how to achieve the possibility to customise the system as much as needed.

7.6 Researching rules, conditions and MC system properties

7.6.1 The MRP process

MRP stands for Material Requirements Planning. It enables a company to calculate the material needed of specific types and at what time it is needed and is therefore used as a scheduling method. The schedules are then used for planning factory floor activities, and often it does not involve any more detailed factory floor control system. The order is released and then processed at whatever pace is possible to attain through the manufacturing processes.

There is a lot of research on MRP presented as journal articles and conference papers, stating that PPC modules based on the MRP principle do inherit qualities from MRP itself that are not desirable. Suri (1998) presents the following dysfunctional effects of MRP.

Physical effects:
- Inflated lead-times are used in an attempt to correct for inaccuracy of load prediction.
- Work In Process (WIP) increases due to the inflated lead-times.
- Last-minute solutions are needed due to inaccuracies, including expediting, overtime, and last minute subcontracting.
- The system becomes unstable, with large changes in schedule resulting from small changes in requirements.
Organisational effects:

- MRP-generated schedules are ignored; everyone knows there is a lot of slack in the schedule.

- A hot-job mentality results, since the only way to know if a part is really needed is if someone is yelling for it.

- Unacceptably long lead-times result in management loading in special orders in less than the planned lead-time. These orders are past due even before the first department can work on them.

- Past due soon has little to do with a given department’s efforts and becomes a meaningless performance measure.

- Employees develop apathy. They feel they can’t contribute to improvements because they are given impossible schedules and are judged by meaningless performance measures.

Notable is that MRP works with fixed lead-times for each department, forcing the department to accomplish this lead-time regardless of whether they are busy or idle (Suri, 1998), which also enhances the problem with MRP based PPC systems; the lack of accurate data, i.e. lead-times and inventory levels. In an MRP system, the time to manufacture a specific product is usually estimated from the lead-times in the plant and the time needed for sub contractors to deliver needed material and components. These lead-times are many times, far from accurate, making the estimation of the total time to manufacture an entire order inaccurate and therefore causing delivery problems.

As stated in chapter 3, there are some strong arguments in defence of the MRP principle. The incorrect uses of MRP based systems are by some, presented as a major cause to the severity of the problems. The way of use, not the design, turns out to be the primary elements behind the deficiencies of MRP (Plenert, 1999a). MRP systems are generally flexible in terms of handling changes of production volumes and being independent of the factory floor layout and therefore being able to controlling manufacturing in different floor layouts. In an MRP system, this flexibility is accomplished in practice by distribution of information (ordering manufacturing start) to a single point and retrieving information from a single point (manufactured order confirmation), which makes it independent from the factory layout. The conclusion originates from observing manufacturing systems. This flexibility is a desired property for the proposed PPC method. Manufacturers must also be able to continuously revise their schedules based upon un-
planned events. To accomplish this, their process and data models, information systems, and communications structure must operate seamlessly in real time (Gumaer, 1996). Practically this means that actual lead-times in the plant has to be monitored, preferably constantly and in real-time.

7.6.2 Two-bin systems and Kanban

The two-bin system is a simple method used for controlling inventory levels. It involves storing the re-order point quantity plus the safety inventory quantity in the second bin and using parts from the first bin. When the first bin empties, that is the signal to order the next re-order quantity (Slack et al, 2001). A two-bin system could be used as a simple production control method.

Kanban could be seen as a development of the two-bin system, being a more advanced and arguably, a more efficient control system.

The kanban system is based upon the levelling of manufacturing of the product needed at the right occasion, aiming for inventory free manufacturing (Olhager & Rapp, 1985).
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In figure 7.7, the principle of single-card kanban control is described. Two stages are shown, but there are similar stages to the left and the right, hence the arrows pointing out of the picture, showing container and card flows.

The system is based on only manufacturing parts needed at the next stage, when the parts are needed. When stage B needs more parts to work on, it withdraws a standard container from the output stock point of stage A. When work centre B has used the parts in the container, it places the move kanban card in a holding area and sends the empty container to the work centre at stage A. The arrival of the empty containers at stage A’s work centre is the signal for manufacturing to take place at work centre A. The move kanban is taken from the holding box back to the output stock point of stage A. This acts as authorisation for the collection of a further full container to be moved from the output stock of stage A through to the work centre at stage B.

Two closed loops control the flow of materials between the stages. The
move kanban loop keeps materials circulating between the stages, and the container loop connects the work centres with the stock point between them and circulates the containers, full from A to B and empty back from B to A (Slack et al, 2001).

Slack et al (2001) states that the rules, which govern the use of kanbans, are as follows:

- Each container must have a kanban card, indicating part number and description, user and maker locations, and quantity.
- The parts are always pulled by the succeeding process (the customer or user).
- No parts are started without a kanban card.
- All containers contain exactly their stated number of parts.
- No defective parts may be sent to the succeeding process.
- The maker (supplier section) can only produce enough parts to make up what has been withdrawn.
- The number of kanbans should be reduced.
- The time period should be made shorter (months to weeks to days to hours).

A station is only allowed to manufacture what is needed at the next station in the flow chain. The well-known Kanban method is based on this rule, so there is a lot of research available for developing such rules further. Another factor to consider is the controlled flow. The manufacturing flow usually needs to be fixed, which is one of the reasons for the stated lack of flexibility of this kind of methods. In short, it is relatively easy to obtain an overall picture of the flow, even without Kanban control. This fixed flow structure of a manufacturing system is not always achievable. Therefore one has to develop a solution, which makes the flows easily monitored, but the monitoring has to be independent of the physical layout of the plant.

7.6.3 Conwip

CONWIP (CONstant Work In Process) is a generalised form of kanban control. It relies on signals, electronically or by cards. The cards are traveling along with the containers through the flow and then as the containers end up as output, the cards are sent back to the beginning of the flow.
The backlog is maintained according to decided standards. It could be generated from a master production schedule. It could also be organised according to a queue principle like first in system – first served.

The general rule that a CONWIP system has to follow is that volumes entering the flow must be of the same magnitude as volumes leaving the flow (input = output).

CONWIP flows would in reality be controlled by the capacity and flexibility of a bottleneck operation. CONWIP could also be combined with kanban, for controlling the materials flow more firmly if needed.

CONWIP allows an easy monitoring of the inventory level in a manufacturing chain, like a line or an established flow of some other kind. The establishment of a maximum workload makes large improvements over a non-controlled chain, or even over a Kanban controlled chain in some instances (Spearman et al, 1990). The possibility to decide a maximum workload for different parts of the manufacturing is therefore recognised as a desirable property for a factory floor control system.

7.6.4 Bottleneck based scheduling

There are also some methods of scheduling based on manufacturing system constraints, which could also be used for manufacturing control purposes. These constraints could be of different nature. Theory of Constraints (TOC) is a well-known principle, aimed at utilising the capacity obtainable from a constraint, a bottleneck as much as possible. TOC aims at finding the constraint, exploiting it as much as possible, subordinating non-bottlenecks to
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the constraint, to increase the capacity of the constraint and then, repeat the entire process (Goldratt & Cox, 1986), always focusing on the process that decides the pace of the output of the factory.

Optimised Production Technology (OPT) is a computer-based tool, which helps to schedule production systems to the pace dictated by the most heavily loaded resources, the bottlenecks. OPT could be used with benefit in an MRP environment since it helps to focus on critical constraints and that it reduces the need for a highly detailed planning of non-bottleneck areas (Slack et al, 2001).

OPT has demonstrated itself to be effective where bottlenecks exist but being not so effective when bottlenecks do not exist (Plenert, 1999b). Bottleneck Allocation Methodology tries to solve this problem by addressing more critical sources of different natures. BAM is a critical resource based capacity planning production scheduler. This means that the resource around which schedules are generated can be changed. The scheduling could then be generated in accordance to resources linked to different corporate goals.

BAM can be focused on material usage efficiency, labour efficiency, machine efficiency or any other critical resource (Plenert, 1999b).

With BAM, the lead-times are not fixed. The same product may be produced in one day on one schedule and in one week on another.

A strength that BAM has over OPT/TOC and MRP is that it uses many different types of constraints as a base for calculations. This creates a need for finding these constraints, their location, their nature and their magnitude.

7.6.5 Conclusions on rules, conditions and properties

The control rules and conditions of the presented scheduling and control methods could easily be expressed as simple IF – THEN – ELSE algorithms. This makes it really easy to implement existing MC systems into the suggested computerised version and also to invent new ones, tailoring them to the present situation at a company.

To profit from using the suggested system (e.g. making savings), the system has to help improving the scheduling function. An observation made in the printing plant and Posten case study, as well as earlier was that scheduling software works better when the scheduling is fed with accurate data. A firm control of the operations on the factory floor would also improve the possibility of complying with calculated schedules. The suggested system has
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therefore to be able to conduct a two-way communication in real-time.
The type of flexibility associated with MRP systems is desirable for the suggested control system. As stated earlier, it has been observed that the flexibility comes from MRPs independence of the factory floor layouts.

Figure 7.9: The few control points of an MRP system, making it more independent of the factory floor layout. Focusing on the control points using figure 7.6.

This independence is harder to accomplish in a more detailed control system since it is connected to more processes in the manufacturing where it applies its control function.
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Figure 7.10: The control points of the manufacturing control system are more numerous and dependent on the factory floor layout. Focusing on the control points using figure 7.6.

This is shown in figure 7.10. Since the manufacturing control system controls flows in detail, it is also more dependent on the flows themselves, which are decided by the factory floor layout and the product structure. The figures 7.7 and 7.8 shows examples of the more detailed control provided manufacturing control systems.

An alternative approach, which is applied in the suggested control system, is to keep the connections to the manufacturing processes, but instead increasing the flexibility by making the software tool more independent of the factory layout. This is discussed more in detail in section 7.8.

Taking bottleneck processes into account is desirable. Results from studying OPT/TOC and BAM support this approach. A strength that BAM has over OPT/TOC and MRP is that is uses many different types of constraints as a base for calculations (Plenert, 1999b). It would therefore be desirable for the suggested control system to be able to locate bottlenecks. As for the suggested
control system solution, this is mainly done by using real-time information retrieval from strategically chosen locations in the manufacturing.

7.7 Standardising the distributed information

The use of standardised information components is a suggested solution for use in the control system. Based on the results from the research part aimed at finding desired system properties (see chapter 4), there are mainly two reasons for this. Both reasons are heavily influenced by the previously presented cost related constraints (see section 7.2 for details).

The first reason is for manufacturing related information to be available at different functions in the company for decision-making or monitoring purposes.

Properly designed, standardised information components are the building block for many available performance measures. Performance measures, as the ones presented in section 4.2.2, are functions of basic pieces of data, some of which could be retrievable from the manufacturing control system in real-time. Therefore the types of data would be useful, not only as monitoring or immediate decision aiding numbers for local manufacturing supervisors, but in many different situations as well as illustrated in figure 7.11 to the right.

The direct linking between basic information retrieved from the manufacturing would also make it possible to accomplish a seamless transition from corporate goals to factory floor related performance goals.
Figure 7.11: Manufacturing related information available at different functions in the company for decision-making or monitoring purposes. This figure is identical to figure 4.16.
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7.8 The customisation capabilities of the system

The partial goal D, introduced in section 7.2, emphasises the need for adaptability of the control system. It has to be adaptable to changes in layouts, production volumes and product structures. This is an area which still requires research. Some suggestions on how to handle these needs are given, but the technical aspects on how to solve the needs are not specified.

Changes in layouts are here exemplified by using a picture showing reconfigurable assembly systems, consisting of standard assembly system components.

![Standard Assembly System Components](image-url)

Figure 7.12: Reconfigurable assembly systems, consisting of standard assembly system components (Onori, 2001).

In this way, the layout could be changed in a very short time, putting similar demands on the control system. The depicted system variants are easy to control, possibly not even requiring changes in the control system. If the principle is applied in an entire factory though, the control situation should be different, forcing changes in the control system structure as well.

Changes in layouts do not have to be physical to cause problems. If the factory is formed as a department layout, changing the flows through the
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factory would pose similar problems to the control system. In a department layout factory, different products take different routes through the plant. This calls for the system to be able to handle many different products and flow routes.

![Diagram of a manufacturing plant with product flow models](image)

**Figure 7.13: Using a product flow model for each product or product family.**

To handle different products and flow routes, the plant has to be modelled. Using different model presentations for different routes would be desirable since it would reduce the complexity of the presentation, as shown in figure 7.13 above.

Changes in the layouts would change the locations of the terminal, which adds a flexibility need to the flow route tool of the manufacturing control system. Since the basic idea is to be able to use a drag and drop tool for the flow modeling, this would not cause any additional problems for the tool itself. There are different manufacturing simulation tools available that work by the drag and drop principle or allowing working principles of similar
simplicity (CreateASoft, 2002; Lanner, 2002; Micro Analysis & Design, 2002; SIMUL8, 2002), so implementing it into software is not a new issue. Adding new product flows to the system could be done by using the factory layout as the basic template. The flow routes would then be added as layers, specifying the exact route for each product or product family, as seen on the right side in figure 7.13.

To be able to execute the control function, the rules and conditions have to be applied.

Figure 7.14: Each product flow model is associated with rules and conditions. The parameters shown are merely examples. The product flow model to the left is from figure 7.13.

Associating each process to a rules form as in figure 7.14 could do this. In figure 7.14 there is an example on how the association could be accomplished. Different parameters could be used to forming the rules and conditions according to which the process should operate. Parameters incorporated into the system should be designed in a way enabling the possibility for the system to act like control methods like Kanban, or to tailor make a new control method variant. In section 7.6, some of the nature of the rules and conditions, as well as some control system properties that are desirable to achieve are mentioned. However, continued research has to be conducted since the results in that section is not enough to form the control system rules and conditions.

A terminal, connected to a database, provides the workers contact with the system. This is put into a larger perspective in figure 7.6 in section 7.5 and figure 7.11 in section 7.7.
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Figure 7.15: Terminals are placed at different locations in the manufacturing. The terminals show what to manufacture, when and how much, based on the rules and conditions.

The terminals are used for presenting control related information to the workers at the site. There is a need to examine the general software design to provide necessary information to the user. For example, information usually distributed informally (see section 7.3.2) should be incorporated into the system. How to accomplish this is a topic for future research.

7.9 Discussing the resulting system

7.9.1 Probable advantages with the system

The greatest need for this kind of solution would arguably be in a situation where the factory layout is changed often and when new products are introduced, as would be the case in for example, an AIP environment (see chapter 3 for information about AIP). There would also be a need for such a system in a department layout factory where changing the physical layouts in order to achieve a better layout, like a line or cell layout, would be expensive or even impossible. The result would be virtual lines or flows, implemented in the control system.

The flexibility of the rules system would also be a benefit when focusing on lowering inventory levels since different parts of the manufacturing could be...
controlled differently, giving the possibility to tailor the control function to
the control need.

Early warnings about disturbances could be vital to operations. The case
studies at the newspaper printing plants and at Posten AB shows this. The
suggested control system would help to distribute information about distur-
bances quickly due to the real-time information handling and distribution.

The system provides means for improved horizontal control information
distribution by making relevant information available when the information
is created. The information is distributed to the different terminals of the
control system, making control information instantly available to people
responsible for the different manufacturing processes. The vertical informa-
tion flow is improved in the same manner and by using data in the system
that is relevant for higher-level performance measures (see section 7.7).

Since the manufacturing is monitored constantly, actual lead-times in manu-
factoring would be available for comparison to the lead-times available in
the scheduling system. The accuracy of the scheduling could therefore be
improved since scheduling lead-times could be updated with data from the
manufacturing.

The constant data retrieval from the manufacturing could be used for finding
bottlenecks in the manufacturing which could be used for planning based on
manufacturing system constraints.

7.9.2 Possible problems related to the system design

Questions concerning the actual day-to-day use of the system should be
raised. The Kanban method originally uses cards and so does the Paired-cell
Overlapping Loops of Cards with Authorisation, POLCA (Suri, 1998)
control method. Large computer systems may cause problems in many ways
and for example, large ERP systems has a tendency to be costly, hard to
implement and use, especially if implemented incorrectly (Davenport, 2000).
Therefore the question if it is appropriate to implement robust control
methods like Kanban, as an advanced and possibly complicated computer
system, is perfectly valid. The system also has to be simple to use. The pre-
study material (see chapter 3) shows that if a system is complicated to use,
data in the system becomes inaccurate due to errors when trying to enter the
data into the system or people neglecting to enter the data entirely.
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As for the suggested control method to result in a complex and disturbance prone system one has to remember that it is far from being such a large system as an ERP system. The amount of data handled is also nowhere near the amount that ERP systems have to cope with. The suggested control system does not have to be integrated into other system, when ERP systems have to be integrated with other systems and into an entire organisation. The suggested control system is a stand-alone entity that does not have to be integrated into other systems physically. It is also limited to one factory and not an entire organisation. These factors reduce the risk for creating a disturbance prone and unwieldy system.

The question if a card based system is easier to use than a computerised version of the same system, has been discussed during AIP project meetings without reaching consensus. The question is not as valid as it may seem, since it is not an issue whether one approach is easier to use than the other. The questions really are; is this approach easy enough to use, is it reliable and what possibilities does it provide? In the case of the proposed control system, the answer to the possibility question is rather obvious. It makes the implementation and use of the proposed system possible. It is not possible to use a card-based version as a base since the data used for control is the same as for system supervision. The flexibility regarding making layout changes and introducing new products would be lost since a card based version would be for example, an original Kanban system, and their lack of flexibility is documented (e.g Suri, 1998). A card-based system would be possible to use in addition to the suggested system, but resulting in a redundancy that is probably not needed and therefore also resulting in unwanted added complexity of the system.

If information is to be retrieved directly from machinery, some problems may occur. As seen in the newspaper printing plant and Posten AB case studies, it is possible to obtain data from automated machinery and integrate the data flow into performance measurement and supervising systems. In the matter of fact, automated information retrieval worked with much less disturbances than when information was to be entered into the system manually by a worker. Problems could occur when using automated machinery from different vendors where there could be different data standards and protocols, making the process of information retrieval more complex.
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7.9.3 Future research directly related to the development of the control system

The future research could be divided into the categories theoretical studies and practical development.

In the former category, there are mainly two topics:
- The rules and conditions design.
- Deciding what kind of information to use in the system.

The rules research is of the same nature as the research presented in section 7.6 with the additional task of finding general base rules, which could be put together to form a system of control rules and conditions.

The information is of a somewhat different nature. General ideas of how to define the information content could be acquired from the sections 4.3 and 4.4 where the selection of concepts to describe manufacturing events is discussed. An extensive amount of research should be available on similar kinds of information distribution issues. Information distribution software is available on the market. In other words, this is a research area where solutions could be available without having to conduct extensive research.

In the latter category, covering practical development, there is the task of putting together the entire system, to solve database design problems, to implement the rules system, to accomplish the flexibility needed etc. Then, the system has to be tested in a manufacturing environment resulting in the need for continued software design work.

Many of the functions defined in the control system are available in software form, in different computer programs. This is positive, since one of the main properties sought after in the system is low cost. If there is software presently available, that could be used and combined into the suggested control system, it could lower development costs as well as purchase, implementation and running costs.
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The critical review is mainly focused on research aspects and methods. Questions directly linked to the results are discussed in direct vicinity to the research itself. This is mainly for achieving consistency for the reader, clarifying and explaining issues related to possible areas of interest. This chapter is therefore related to chapter 2, presenting the practical use of the material presented there.

8.1 Critical review of the research areas

The relevance, validity and reliability of the research work are questioned as well as the validity, quality and usability of the results. The critical review is based on the section 2.3, where the criteria are presented.

In all the research, measures have been taken to accomplish high levels of validity and reliability, following the guidelines given in earlier in section 2.3. Data triangulation, investigator triangulation, theory triangulation and/or methodological triangulation have generally been used when applicable. If the levels of validity and reliability are questionable, it has been commented in the following sections.

The degree of reliability is mainly ensured by describing and explaining research goals. Since a large part of the research is based on interviews, conducting the same research and coming up with the same results could in some cases be hard, resulting in a lower level of reliability.
8.1.1 The main objective

The objective is presented in chapter 1 as:

*The objective of this research is to provide means for accomplishing and upholding high manufacturing system performance, aiding in the task of reaching individual company-specific performance goals.*

The objective could be seen as general or wide to its nature and it leaves a large number of possible ways to accomplish a solution.

The validity of the objective could be argued for in many ways. First one may use the large number of research projects aiming for solving problems that originates from similar objectives. The sheer number of such projects is extremely hard to appreciate though. However, improving and upholding high manufacturing system performance is considered to be important by many. Increasing levels of competition is a very often-found reason. The aiding of increasing and upholding high manufacturing system performance in itself, is therefore considered to be a valid task. Since performance goals may vary over time and between different companies, focusing on aiding the reaching of company-specific goals is also valid.
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The number of available methods and other research results covering this objective could be used for questioning the necessity of another research project in this area. Since the manufacturing world constantly changes in many affecting areas (economic, technical etc), new possibilities could erupt, which makes constant research of the area valid.

8.1.2 The Assembly-Initiated Production research

![Diagram showing the Assembly-Initiated Production research goals]

The partial research goals 1 and 2 were defined as:

1) Study the concept of a strategy based on the initial ideal performance goals and give basic guidelines for explaining the strategy. The details on the ideal performance goals have been presented in section 1.2.1.

2) Study what would be needed in the form of technical and organisational means for implementing highly flexible manufacturing in general and based on the developed strategy in particular.

The relevance of the partial goals relies on the relevance of drafting the first strategy goals in chapter 1 which also is dependent on developments affecting the world of manufacturing.
Critical review and future research

In chapter 3, there are three lower level partial research goals presented (A-C).

A) To clarify whether there exists a set of basic constraints, which must be satisfied prior to the implementation of an AIP-based system.

B) To pinpoint the driving factors which influence the performance of AIP. These may subsequently be used to form an implementation and evaluation method for AIP.

C) To present a first draft of such a method. The proposed method will not be tested in this project and will likely require some rework to be entirely useful in the intended ways. This will be considered as future research.

Goal A and B are arguably relevant if an AIP strategy is to be developed since they then have to be solved.

The partial goal C was changed into researching a more general manufacturing system design method, which is presented in chapter 4, 5 and 6. The reason for that is to increase the relevance of the research. Since the relevance of the AIP strategy could change, virtually over night due to reasons stated earlier regarding changes in the world of manufacturing, an implementation and evaluation method coupled directly to AIP would be made useless if AIP became impossible to use.

Since the research to a large extent is based on interviews and single observations made over a relatively short period of time, the validity of the research could be questioned. However, initial observations have been supported by new observations and literature studies over a period of three years, increasing the validity. The surveys and case studies have been carried out at different companies. Over a period of almost three years, ten companies have been studied and people from 19 companies have provided information, the ten first included. Details about this are given in chapter 3. Practical studies have been complemented with theoretical studies, providing means for triangulation, and understanding of different issues in order to strengthen the validity of the research.

The reliability could be questioned, also on the basis of conducting parts of the research as interviews. It may not be possible to recreate the interviews and factory studies entirely. To strengthen reliability, goals and intentions have been presented in order to make it possible to conduct similar studies, although it has to be noted that results may change since manufacturing affecting factors outside the control of the manufacturing company, may change over time. Intentions with the AIP strategy are described which
makes new AIP focused studies doable. The results could however change. The reason for that is development in economy and in technical advances since the original studies have been made, making different solutions than those found possible.

For deciding the quality of the AIP strategy, it has to be tried and tested, for example by implementing it or by simulation. This has not been done and therefore the quality cannot be heavily argued for.

8.1.3 The design method research

![Diagram showing the design method related research goals.]

**Figure 8.3: The design method related research goals.**

Partial goal 3 was defined as:

3) *Develop a general design methodology, aiming at supporting strategy implementation.*

This goal originates from partial goal C and has been argued for in the sense of not developing an AIP specific method.
Arguably, there are many manufacturing system design methods available, focusing on different tasks, areas or types of desired manufacturing system properties. The focus of this research has been the early system design phase where a lack of design aid tools has been identified. This lack of aiding tools makes the design method research relevant.

To be able to develop the intended method, partial goal D was formed:

D) *The development of a general method structure and performance parameters that could describe the performance of a manufacturing system, regardless of development phase and organisational level.*

For this goal to be relevant, some prerequisites have to be met. First, it has to be possible to describe manufacturing situations accurate enough by combining different concepts as described in chapter 4. A physicist could describe all physical phenomena by using only a few low-level concepts (see chapter 2 for explanations). Manufacturing consists of different physical phenomena, hence manufacturing could be described by using the same different low-level concepts. One could discuss if it is practical or even suitable to use the same basic concepts as used in physics when describing other concepts or simple world phenomena. Therefore some manufacturing related concepts were introduced in chapter 4. They have only been tested on simple theoretical cases, not on practical real world industrial cases, which makes them more uncertain.

The goal also includes the development of a structure that could describe a manufacturing system. The suggested structure, introduced in chapter 5, has been tested when conducting different industrial cases. In parallel to data gathering, the investigated manufacturing system has been drawn as tree structures as presented. Notable is that the resulting tree structures have not been used as a tool in other research since it would add uncertainty to the results. The research has been conducted in parallel with different goals, not together. The usability of the tree structure was tested and proven useful and simple, although is has to be noted that the test cases were rather limited in size, small departments being the largest test subject.

The relevance of using the suggested FPA model in favour of the models created by using the IDEF method has been argued for in section 6.2.1.

Point of views, background and theoretical perspective are clarified, which strengthens the reliability of the method research. The used theory and the detailed description of reasoning and theory used strengthen the validity of the research. As mentioned earlier, the research has to be tested practically in order to review the quality of the results.
Partial goal 4 was defined as:

4) To provide means for performance improvement possibilities in manufacturing by introducing a new MC system, focusing on acting on events and therefore leaving out planning issues.

Early in the pre-study phase, manufacturing control was found to be an area important to put research effort into if overall manufacturing performance was to be improved. This is argued for in the chapters 3 and 7, which supports the relevance in conducting MC related research in general.

Pre-study results put the research focus on some specific targets, based on industrial needs. These targets became partial goal E:

The goal with this research is to develop a structured manufacturing control system concept, with main properties being flexibility in the sense of reconfiguration and use, as well as real-time data distribution and acquisition for use on the factory floor. Main properties to build into the system are:

- Adaptability: It has to be adaptable to changes in layouts, production volumes, and changes in the product structures.
- Low cost: it has to be cheap to buy, implement and use.
Critical review and future research

- To fit into an already existing PPC environment: When asking subjects for desired characteristics of a control system, many requested that investments already made should not be made obsolete. This demand has been extended into that it should fit different scheduling environments.

- To provide relevant and accurate data.

- To be simple to use for operators and management alike.

Their validity has been strengthened by using multiple sources of evidence, by doing explanation-building and by using replication logics in different cases (see section 2.3 for more details). Providing the sources for the information strengthens reliability but reliability is a problem in this part of the thesis as well. Large parts of the results originate from interviews, where it may be impossible to replicate the studies entirely.

This partial goal has also been argued for in chapter 7, proving it relevant. Although one may question if MC is influencing the performance of manufacturing enough to be given such importance as it is given in this thesis. An example useful when discussing this issue is the Lean Production and Just In Time related control method Kanban. Kanban control is often given a large amount of credit for lowering inventories and making manufacturing more efficient in general. Looking at the requirements the use of Kanban puts on the manufacturing system in for example, the demand for high and even manufactured volumes and an ordered manufacturing flow, it is questionable if it really is the Kanban system in itself that provides these efficiencies. These are desirable properties from a manufacturing system that could provide these efficiencies. It is however possible that these properties are not reachable and therefore similar properties has to be achieved by using other means. Also notable is that designing and using Kanban was a part of a larger system strategy where all the means were focused on a specific set of goals. The partial goal E supports a flexible system, which could be used in many different situations and therefore most likely in accordance to many different strategies. This would make the system fit for use by different companies with different strategies in reaching their goals or in a situation when the strategy is to be able to make quick and considerable changes in the manufacturing system. Therefore, conducting research on an MC system with the properties described in partial goal E is relevant.
Chapter 8

8.1.5 Comments on the research strategy and methods used

According to Yin (1994), the softer a research strategy, the harder it is to do. The objective could be seen as loose or soft, as formulated. A softly formed objective does not necessarily mean a soft research strategy, but focusing the research on such an objective could be complicated. The formulation of the partial goals is closer oriented to practical solutions than the objective, giving the direction of the research. The partial goals are formulated to provide the possibility to form a harder research strategy focused on the area-specific goals.

As for methods used, action research should be a suitable method to use in the research presented in this thesis, which should have been evaluated for use. Considering the resources available, action research was never a realistic alternative. Not using action research could however be seen as a weakness of the overall argumentation for the results.

8.2 Contribution of the research

The strategy related research is focusing on accomplishing high performance manufacturing systems where flexibility is of outmost importance, but also emphasising the lowering of inventories and the shortening of delivery-time. If these are important parameters for a manufacturing company, the AIP strategy should be a possible aid in designing or improving the manufacturing process. The presentation of available solutions presented in chapter 3, should provide means for the creation of an action plan, focused on the implementation of AIP.

The manufacturing system design method research presented in the chapters 4-6, gives a platform for continued development of a design method. As stated in chapter 6, the method has not been tested in a live manufacturing case. Such tests should be conducted before considering the method complete. It is probable that some changes or fine-tuning would be necessary.

The focus of the method is for use in an early design phase, when there is no actual system available. This is identified as an area where there is a lack of actual design tools, making the contribution of the research more considerable.
Critical review and future research

In addition to what has been presented in the form of research goals and achieving them, an intended contribution of the research has been the re-thinking of manufacturing as a process. Manufacturing research is often very solution oriented, looking at for example, the use of different solutions, the success of different solutions and the suggesting of different solutions based on the successful use of solutions by others. The research presented in this thesis, especially the parts presented in chapter 4, is an attempt to put manufacturing in a different viewpoint. The main focus being put on viewing the properties of a manufacturing system and the properties needed to accomplish high performance manufacturing.

Manufacturing control is an area where there is room for improvement. In the strategy related research, a lack of control methods that can keep inventories down and at the same time has the required levels of flexibility needed, was found. The suggested solution could provide the functions and properties of different methods like Kanban if wanted, making the control system very flexible. A theory foundation and first design for a manufacturing control system has been provided, and if implemented, it could provide the control function in a highly changeable environment.

In the manufacturing control related research, a different view than usual on the subject has been used. The function provided by manufacturing control and the desired properties have been the primary focus, not other available methods. This could provide ideas for continued research on manufacturing control system design conducted differently than usual, increasing the possibilities to design control systems more focused on specific tasks or desired properties.

8.3 Future research

Since the evaluation of the AIP strategy presented in chapter 3 is mainly of technical nature, economical evaluations should be done to shed some light on the subject of when to implement and use it. One problem is that world conditions may change over time, making economical calculations somewhat erratic. However, making calculations on a number of relevant cases would be an aid when deciding on practical testing of the strategy.
The design method package is still rather loosely defined and developed. Some method components have to be researched and developed further and the entire package of components has to be tested together as a unit. The two method components that has to be developed further are:

- The definition of the basic concepts, presented in section 4.4.1 should be looked into since there may be more concepts needed to describe a manufacturing system in an easy manner. Guidelines for choosing and defining concepts are given in this thesis (section 4.3).

- The further development of a tool for helping to decide the relationship between different performance deciding factors and different manufacturing areas. Presently, the matrix form is used as described in section 5.3. This tool is to provide the user with a link between low-level concepts and intended improvements, which makes it extremely important to develop properly.

Continued development of the manufacturing control system is of a practical nature. The main project would be to put together a computerised version of the system. Since one of the ideas is to minimise costs, already available computer software should be tested. For example, there is software available for monitoring manufacturing processes in real-time, which may be used in that function and it may even be possible to modify it to function as a control system as well. Also the computer software that implements control rules has to be designed and programmed.

There is also some continued research to be conducted on what information to use for storage and distribution. The presented research suggests a similar approach as in the design method; to use standardised concepts, which can describe the situations to be controlled in a manufacturing system.

One notable insight acquired when conducting PPC related research through the entire project is that a considerable part of the literature reviewed, discusses the implementation of control methods that has been available for a long period of time. The most common example has been the Kanban control method, but the Conwip method has also been covered, although less frequently. It is this authors firm standpoint that new methods should be developed, which may be tailored for a specific situation, by looking at control properties in the form of rules and conditions instead of merely trying to implement available methods. The suggested continued research in
this area is therefore to conduct deeper research into the actual working procedures of manufacturing control methods. It has to be mentioned though that some research, similar to its nature, has been conducted when combining for example Kanban and Conwip, tailoring the behaviour of a manufacturing flow to lower inventory levels further.
Chapter 9

A

AIP project group. 2001, Discussions on AIP, held at the Royal Institute of Technology. Present at the meeting: Kjell E Björklund, ABB Production Development; Reine Alemar, Volvo Truck Corporation; Ola Sjödin, Atlas Copco Tools; Jan C Larsson, ITT Flygt; Anders Arnström, KTH; Peter Gröndahl, KTH; Anders Karlsson, KTH. Stockholm. Sweden.


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