THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

A study of process planning for metal cutting

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Abstract

Process planning as a function for competitiveness is often neglected. However, as an intermediary between product development and manufacturing, it holds a key function in transforming product specifications and requirements into a producible process plan. Demands and requirements should be met concurrently as manufacturing costs and lead times are minimised. The focus of this thesis is the act of process planning, where the use of better methodologies, computer-aids and performance measurements are essential parts. Since process planning has the function of transforming demands and requirements, changing customer and regulative requirements are vital to regard. Since environmentally benign products and production increases in importance, the research presented in this thesis includes a CNC machining cost model, which relates machining costs to energy consumption. The presented results in this thesis are based on quantitative and qualitative studies in the metal working industry.

This thesis has contributed to an enhanced understanding of process planning to achieve better performance and important areas for improvements. Despite a 50 year history of computerised process planning aids, few of these are used in the industry, where manual process planning activities are more common. Process planning aids should be developed around the process planner so that non-value adding activities, such as information management and documentation are minimised in order to allow more resources for value adding activities, such as decision making. This thesis presents a study of systematic process planning in relation to perceived efficiency. This correlation could however not be verified, which opens up for further studies of other possible explanations for process planning efficiency. Process planning improvements in the industry are difficult to make, since there is little focus on process planning activities and limited knowledge about actual performance hereof. This means that measures taken regarding process planning development are difficult to verify.

Keywords: Process planning, CAPP, CAM, efficiency, performance, green manufacturing

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Staffan Anderberg

Trollhättan, November 2009

Appended papers

Paper I — Anderberg, S., Beno, T., Pejryd, L., 2008, *Production preparation methodology in Swedish metal working industry - a State of the Art investigation*, Swedish Production Symposium 2008, Stockholm

Paper II — Anderberg, S., Beno, T., Pejryd, L., 2009, *CNC machining process planning productivity – a qualitative survey*, Swedish Production Symposium 2009, Göteborg (submitted)

Paper III — Anderberg, S., Beno, T., Pejryd, L., 2009, *A survey of metal working companies' readiness for process planning performance measurements*, IEEE International Conference on Industrial Engineering and Engineering Management 2009, Hong Kong

Paper IV — Beno, T., Anderberg, S., Pejryd, L., 2009, *Green machining – improving the bottom line*, 16th CIRP International Conference on Life cycle Engineering, Cairo

Paper V — Anderberg, S., Kara, S., Beno, T., 2009, *Impact of energy efficiency on CNC machining*, International Journal of Engineering Manufacture (accepted for publication)

List of acronyms

APT:	Automatic Programmed Tooling
BLISK:	BLaded dISK
CAD:	Computer Aided Design
CAM:	Computer Aided Manufacturing
CAPP:	Computer-Aided Process Planning
CE:	Concurrent Engineering
CNC:	Computer Numerical Control
ERP:	Enterprise Resource Planning
KBE:	Knowledge Based Engineering
NC:	Numerical Control
PDM:	Product Data Management
PLM:	Product Lifecycle Management
SME:	Small and Medium size Enterprises
SPC:	Statistical Process Control

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1 Introduction

1.1 Background

Due to the extensive technological development of Computational Fluid Dynamics (CFD), component solutions are generated that enforce very high demands on the employed manufacturing processes. One example is doubly curved blades to the fan, compressor and turbine parts of a jet engine. A BLISK (BLaded dISK) is made from one solid workpiece where each disk blade is formed by milling operations. The result is a complete BLISK (fan or compressor) in one piece, compared to the traditional manufacturing technology where each blade is mounted (welded or screwed) on the centre shaft. The result is a fan with enhanced lifetime, lower weight, and less tendency for imbalances and vibrations. In an aeroplane jet engine this can reduce the fuel consumption. The increased process planning complexity that the BLISK technology imposes e.g. increased geometric complexity, surface tolerances and reachability problems during machining in combination with machine configuration and clamping, creates a need for improved process planning working methodologies. Efficient product realisation requires large quantities of information regarding machine tool, cutting tool selection, machining parameters, machining strategy and clamping. The parameters defined and decisions made during process planning to a great extent dictate the productivity and cost efficiency of the machining process.

Central produktionsteknik (production technology), which is the department that handles the process planning in Volvo Aero Corporation in total employs 121 persons. In a company with 2300 employees, this is a considerable part. Consequently, it is important to ensure that processes are carried out efficiently. Furthermore, process planning for a major aerospace component is very resource intensive, not only because the aerospace industry is obliged to provide documented product performance and guarantee traceability of individual components with respect to the manufacturing process, but also because the materials are difficult to machine and errors are costly etc.

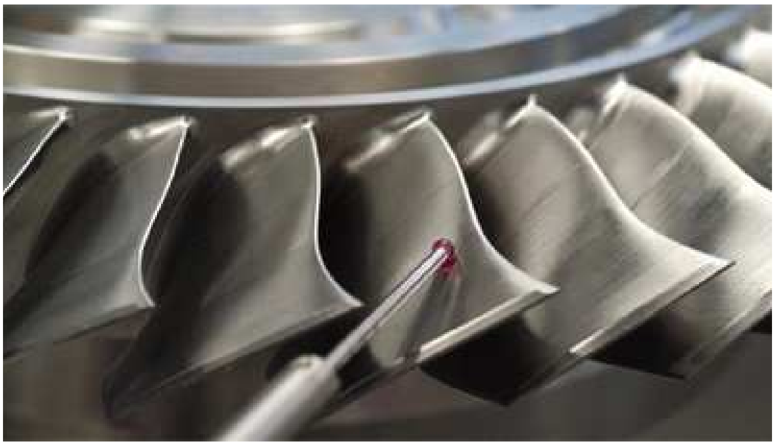


Figure 1. BLISK

CNC was one of the most important developments for the manufacturing industry in the 20th century. It is an enabler for mass production as well as small series production of almost any geometrical shape. However, one of the major drawbacks of CNC machining is the CNC programming, which requires skilful programmers, who not only should manage CAD/CAM or NC programming, but also have extensive knowledge about machining (Yeung, 2003). Machining knowledge includes knowledge about tool selection, machining parameters, vibrations and cooling etc. Whereas tool paths (in the form of NC code) can be generated efficiently by most CAD/CAM systems, the technological preparation often is tedious and requires much data, information and decisions to enable efficient machining processes.

Process planning is often seen as an art and not a science (Halevi, 2003). As a consequence there is little uniformity of working methodologies, which means that two process planners will probably not deliver the same process plan for a given part and set of requirements, although both plans may fulfil specified requirements. Modern technology has radically changed the required human skills. Due to the more intellectual activities involved in many jobs, the need for strength and motor performance have become less important. Intellectual skills such as judgement and decision making have become crucial human elements (Slovic, 1982). Today, due to a shift from more labour intense work (blue-collar) to more intellectual work (white-collar), human productivity is becoming more and more a matter of efficient information processing and decision making (Howell, 1982). The productivity of today's society is as a consequence of aforementioned, depending more on cognitive processes than on physical power of individuals. The main research effort in the area of lean production has been put into the physical production itself, whereas less attention has been paid to the leanness of the production planning phase. The importance of also including engineering work into account was studied by Ref. (Murgau, Johansson et al., 2005), where the interaction between physical work and information handling was studied.

1.1.1 The importance of process planning

The design phase often comprises a smaller part of the direct product cost compared to e.g. material and manufacturing costs. However when its potential for cost saving and efficient production is regarded its total influence on subsequent activities is crucial for the total cost (Figure 2). The design phase not only consist of design and engineering work related to product development, but also include production and process planning/design, which have a similar relation to the total product cost. More time and resources invested in process planning will have influence on manufacturing cost, time and similarly the total product cost. This may be of less importance for small/single batch manufacturing, but with the increase of batch size, this will gain in importance.

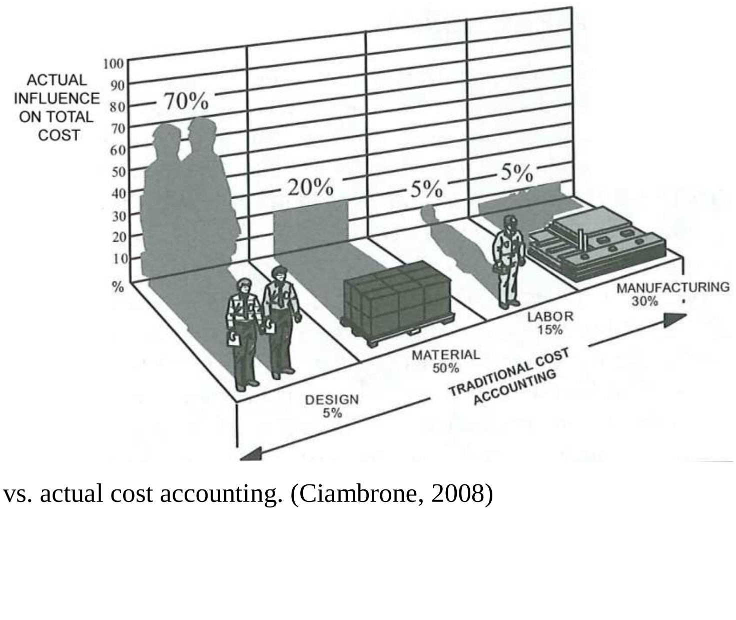


Figure 2. Traditional vs. actual cost accounting. (Ciambrone, 2008)

Figure 3 illustrate the relation between machining time and thinking time. Thinking time is here the time spent on process planning, to analyse the problem, finding solutions etc. It is thus seen that if resources are spent on the planning of the machining process, it will be performed more efficient, and since it has a direct relation to machining time, various related costs, and thereby the machining cost and total manufacturing cost can be lowered. Machining cost reduction can in this perspective in general be regarded as coming to a price of increased process planning cost. This means that the ratio between the two must be evaluated to see when it is beneficial to spend additional resources on process planning efficiency and when it is not (Figure 4). The aim of process planning improvements is to reduce the cost for planning activities, while achieving the same machining results or better (Figure 3). There is a wide range of approaches for making process planning efficiency improvements. There are many researchers and authors of technical papers that aim at developing process planning from various viewpoints and objectives (Bagge, 2009). The most common approaches include CAPP (automation of process planning activities), expert systems, model driven functions and working procedures. There is also much research invested in developing better algorithms for tool path generation and optimisation of machining parameters under certain cutting conditions.

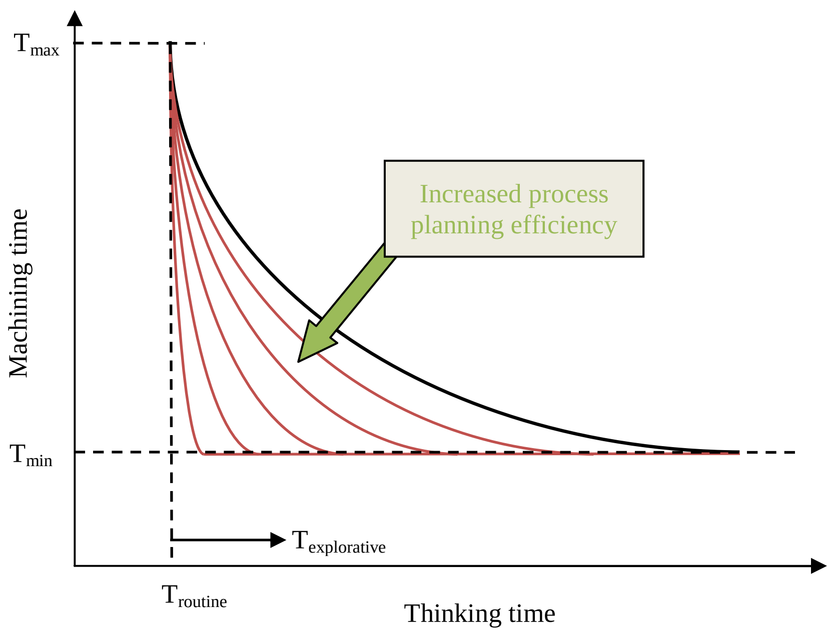


Figure 3. Machining time as a function of process planning thinking time. Adopted and modified from Ref. (Halevi and Weill, 1995)

The cost of process planning versus the cost reduction in machining time is basically the marginal cost for reducing the cost during machining. Simplified, this can be illustrated in the formulas as follows (Figure 4). It is desired to ensure that process planning activities are profitable in a machining cost perspective. (Figure 4). Here $C_{PP} = L_{PP}(T_{routine} + T_{explorative})$, $C_M = C_m N(T_M - \Delta T)$. One seeks to keep the marginal (variable) process planning cost lower than the achieved machining cost savings, to make additional process planning activities economically motivated. This is expresses as $L_{PP}T_{explorative} < C_m N \Delta T$.

Where:

C_{PP} -	Process planning cost for a certain machining operation
L_{PP} -	Hourly process planning cost rate
$T_{routine}$ -	Routine planning time for a certain machining operation
$T_{explorative}$ -	Explorative planning time for a certain machining operation
C_M -	Cost for a certain machining operation
N -	Batch size
T_M -	Machining time for a certain operation
ΔT -	Machining time saving due to explorative process planning time
C_m -	Hourly machine operation rate

As seen in Figure 4, higher process planning cost can be economically motivated with increasing batch sizes.

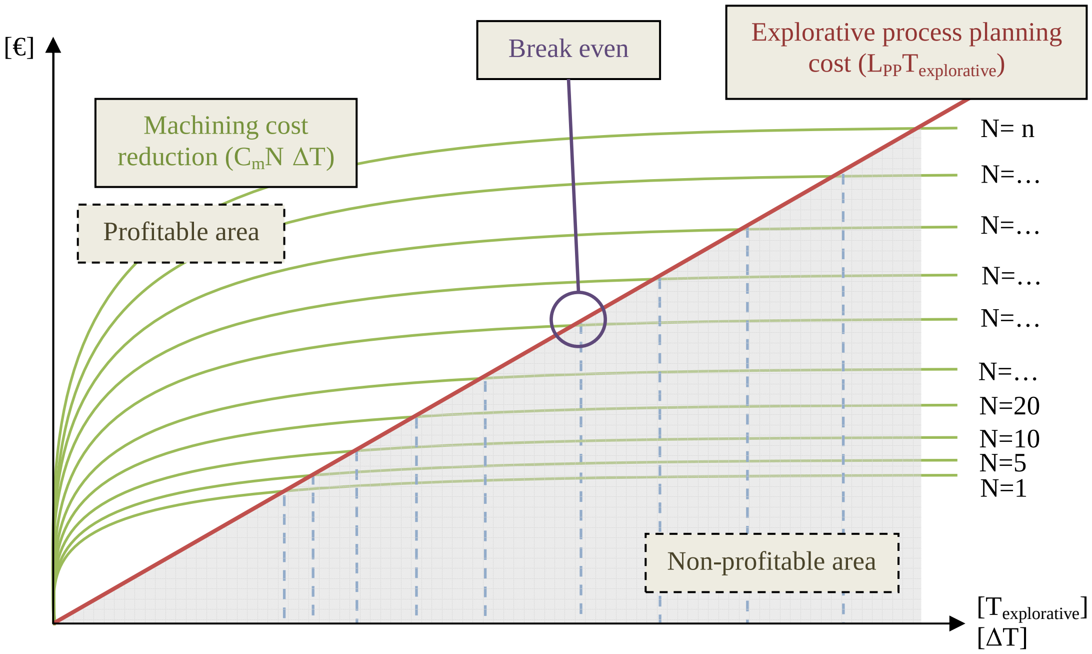


Figure 4. Explorative process planning cost versus machining cost reduction.

1.2 Aim and scope

As the title of the thesis indicates, the aim is principally to study and understand process planning. The objective is mainly twofold. First the process planning function is investigated regarding use of aids to manage and control in order to achieve increased process planning performance. The second objective concerns the changing demands and requirements of process planning, which here is focused to environmental aspects of machining and energy consumption specifically.

This thesis will focus on metal cutting processes; milling, turning and drilling operations, which are material removal processes. Other manufacturing processes include various casting, forging, extrusion and welding processes. Some of the knowledge presented in this thesis is probably applicable to these processes as well, but that is outside scope of this thesis. There are good reasons for mainly focusing on the first group since the majority of machines and production volume is transformed using this technology (Halevi and Weill, 1995). Material removal processes are in their features flexible regarding batch size, materials and geometric freedom. This implicates that the present situation is likely to be reinforced in the future due to the higher demands on manufacturing flexibility.

1.3 Research questions

Aforementioned research aim and focus can be stated in three research questions that this thesis seek to answer. These are:

- How *are* processes planning aids used in the metal working industry, in order to increase process planning performance through the automation of manual work and better information management?
- How *should* these process planning aids be used, to increase process planning performance?
- How do future and changing demands and requirements on companies influence process planning (i.e. environmental demands in this thesis)?

1.4 Disposition of the thesis

The thesis outline follows the main topics; Chapter 2 presents the process planning environment - principal constraints that operate on process planning internally and externally. Chapter 3 provide enhanced understanding for the act of process planning. Chapter 4 contains the main results from appended papers and discussion in line with the thesis topic. Chapter 5 concludes the thesis, while chapter 6 offer insight into future work and research questions with respect to drawn conclusions.

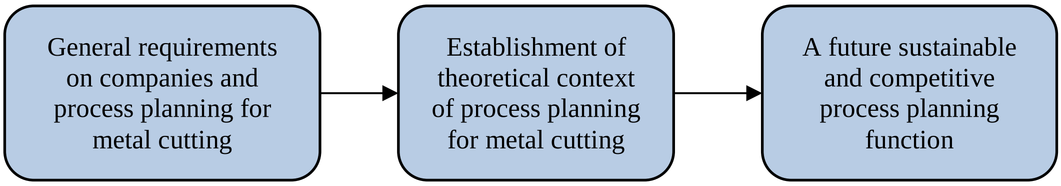


Figure 5. Disposition of thesis

1.5 Research approach

This thesis is based on a number of principles that are essential to regard when studying the subject of process planning improvement for increased performance.

1.5.1 Productivity improvements

In every organisation and business unit, three principal types of losses can be identified that influence productivity (Saito, 2001):

- *Method losses* – due to inefficient methods excess personnel and machinery are needed;

- *Performance losses* – due to low performance of personnel and equipment, losses in potential productivity follows;
- *Utilisation losses* – underutilisation of personnel and/or equipment leads to losses.

The aim and scope as presented in chapter 1.2 of the research is mainly within the field of method losses. To study the performance of individual process planners can be categorized under the psychosocial and work organisational study field and is excluded from the scope of this thesis. Here the focus is on describing how systematic working methodology can aid the performance of the individual process planner and process planning function.

1.5.2 Process performance

In line with aforementioned, this thesis will focus on efficiency as the main performance dimension. However, effectiveness is a vital part of process planning performance, thus forth mentioning. A distinction between two principal performance measures is made in this thesis. The first is the performance of the planning process itself – regarding resource use and can be regarded as *the process planning efficiency*. The other is the performance of the outcome of the planning process; *the process planning effectiveness*, which and describes how efficient the generated process plans are to produce intended products. Both of these performance measures are important in such ways that it is pointless to have a lean/efficient process planning function if the outcome does not generate efficient and competitive machining operations. On the contrary optimal machining operations cannot be justified at any cost, especially if the product series are small, as discussed in chapters 1.1.1. The main thesis focus is on process planning efficiency, but effectiveness will be included where relevant.

1.5.3 Automation

An automation perspective is vital to better understand process planning efficiency improvements. Automation of labour intensive manufacturing has persisted throughout the history of mankind, but accelerated with the industrialisation and introduction of computers in the industry. The main driver behind automation is cost reduction, but can also be motivated through a quality perspective and consistency of output. It can also be motivated by work environmental issues. The automation area has followed the development of new technology, that cost efficiently enables automation of operations. Non-production processes have not been automated in the same extent until rather recently with the development of efficient computer systems that can manage large amounts of data and complicated calculations (e.g. FEM, CFD, CAx). Considerable steps have been made in a process planning context, where computer aids such as CAM, CAPP and PLM systems aims at automating different activities of process planning work. These computer aids are more in detail discussed in subsequent chapters. Common with automation for manufacturing processes, the automation of engineering work also implies a flexibility loss, since the human mind and body, probably is the most flexible machine available. When a process is automated, bits of flexibility are lost. The usually rather high investment threshold is together with aforementioned flexibility loss one of the main drawbacks of automation.

1.6 Research methodology

In research of a parts or wholes of a company, the organisation itself cannot provide answers to surveys and information must accordingly be provided by the individuals working within the organisation (Forza, 2002). It is therefore important that the right people are approached when a survey is conducted so that the research is complete in respect to scope and reliability.

Qualitative and quantitative research methods are often put against each other, where the latter is often seen as superior in generating empirically reliable and valid results. Albeit inherent differences, both methods contribute unique and complementary ways to theory generation and testing (Bachiochi and Weiner, 2004). The differences between the two approaches are present in philosophical orientation, question development, involvement of the researcher, tools, flexibility, and contextual influences. In many cases both qualitative and quantitative methods can complement each other and give stronger results (Bachiochi and Weiner, 2004).

The research conducted in this thesis comprises both methods, thus a description and an outline of each areas contribution and characteristics will be included here:

- *Quantitative studies* - Mailed questionnaires have the benefit of being cost efficient, can be completed when respondents have time, can ensure anonymity. On the contrary they often have a lower response rate, involves longer lead times and lack of open-ended questions. (Forza, 2002)
- *Qualitative studies* - Qualitative studies stem from the social sciences, but have been adapted to many other fields as well. Qualitative research is distinguished from quantitative research mainly in the act of observation and analysis. Observations are often carried in natural setting and through structured and semi-structured interviewing techniques. (Locke and Golden-Biddle, 2004) The advantage of conducting interviews are the flexibility (question sequencing, details and explanation), which enables more complex surveys to be carried out (Forza, 2002). The analyses are consequently performed mainly with verbal and non-numerical language to describe the topic of interest. (Locke and Golden-Biddle, 2004)

1.6.1 Experiments

Although this thesis does not have an experimental approach – paper V includes a model which was supplied with experimental data. These machining experiments were carried out in the manufacturing lab at School of Mechanical and Manufacturing Engineering at the University of New South Wales, Sydney.

2 Process planning constraints

Process planning is the work of transforming a set of product specifications into a production/process plan that meet these specified requirements. The act of process planning includes decisions and selection of e.g. the sequencing of operations, tools, fixtures and machining parameters. The process planning act is in more detail discussed in chapter 3. The constraints that influence the process planning function can be separated into two principal categories; internal and external depending on their nature. It facilitates the understanding of the different demands if this demarcation is made, since each level are associated with a certain type of requirements, which constraints the process planning work. It also concerns the process planners' possibilities to affect the constraints. The differentiation made here is (Figure 6):

- *External level*: The external demands are here defined as those demands and requirements that constrain the process planning function, but cannot directly be influenced by the process planner. It can be regarded as environment variables in a process planning context. The external demands consists to a great extent of customer demands (i.e. speed, time, quality, cost but also environmental) as projected on the function of process planning. It also includes standards and regulations (e.g. environmental and work environmental)
- *Internal level:* The internal level refers to those demands and parameters that constrain the process planning function and can be directly or indirectly influenced by the process planner. It includes allocated resources and time that refer to the organisation. The internal level also refers to the decisions made by the process planner and more concerns the technological context of the planned process (see chapter 2.2 and 3.1)

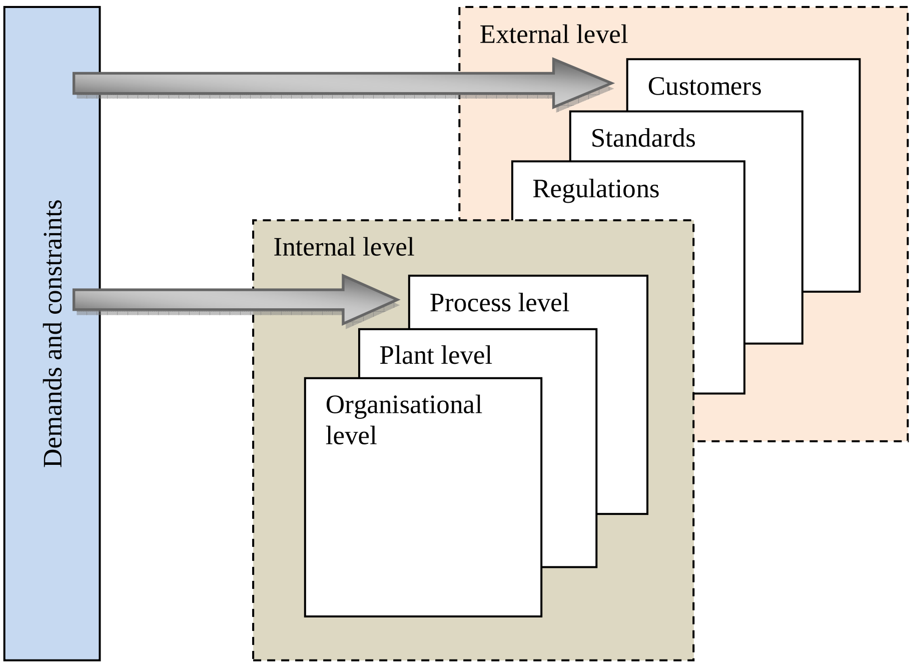


Figure 6. Each level of process planning is connected to a certain set of mechanical, physical, environmental, economical, customer constraints and demands.

In general there are a number of dimensions that influence all producing organisations that are the fundaments for performance. The priority between these performance drivers has shifted throughout the history and is continuously doing so. The traditional ones are cost, quality, delivery/time and flexibility, but environment can also be included since its importance is growing and cannot directly be categorised under any of the other (Figure 7). Which one of the performance dimensions that is most important is a matter of competitive positioning of the company, although all dimensions are important to some extent (Hallgren, 2007). To a great extent the performance drivers relate to customer demands, since it is the customers that ultimately define the priority and value of the drivers. The performance drivers thereby define how operations[1] in the company is carried out, not the least process planning, which have influence on all of them. Efficient process planning can be one of the key functions to remain competitive in a changing environment. For a supplier without own design function, process planning is basically the main function for competitiveness alongside a lean and efficient manufacturing unit. Process planning, as the bridge between design and manufacturing is therefore important since it not only have influence of the product quality, but also on direct manufacturing lead time and the time-to-market.

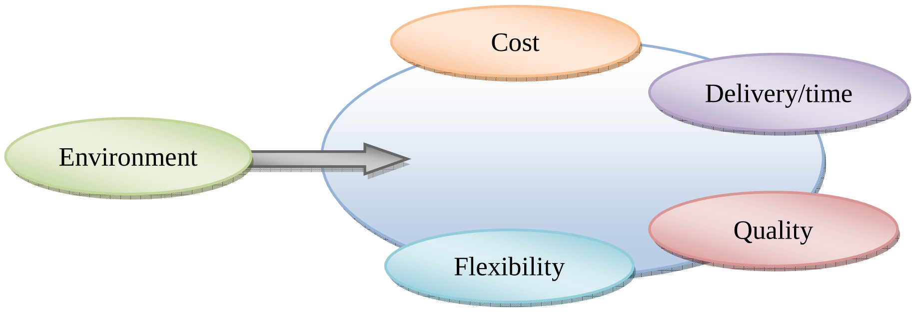


Figure 7. Performance drivers.

2.1 External constraints

Customer demands are the main imposer of the external constraints by stipulating their needs, requirements and desires, which a company must act on to be contracted. Customer demands explicitly or implicitly concern all the performance drivers. Regulations and standards restrict the process planning activities or enforce certain steps and/or documents to be completed. Many companies are certified according to quality management standard ISO 9000 and environmental management standard ISO 14000, which impose restrictions also of process planning.

The position in the supply chain or network influences the applied constraints. Many metal working companies act as suppliers or sub-supplier in the supply chain, which often means that they do not have direct contact with the end customers, but are contracted by a manufacturer, which defines the prerequisites for giving an order to a supplier. The supplier can have or not have component design responsibilities, which will influence how constraints apply on the supplier at large but also the process planning function. If the supplier does not have design responsibilities, there are fewer possibilities for making design changes for

[1] operation should in this context not be confused with the physical machining operation (also used in the thesis), but rather the act of transforming input into useful output (Meredith, J., R. (1992) *The management of operations: a conceptual emphasis*, John Wiley & Sons, Inc.).

manufacturability or to adapt product to the machines and manufacturing system available. Whether a longstanding relation between manufacturer and supplier exists also have influence on process planning constraints and the possibilities to ensure high process planning efficiency. If many temporary business relations exist, the input (drawings and models etc.) to the supplier will vary; i.e. inhomogeneous input, which will have implications for the possibility for automating process planning activities. For In-house designed products it is easier to guarantee the interface between design and process planning. This is discussed further in chapter 3.5. Process planning is also affected by the use of 3D models, which is an enabler for virtual process planning regarding simulations and efficient data and information transfer. The product itself are also connected to certain constraints regarding the act of process planning, since product geometry and material roughly govern the process planning lead time. Geometrical complexity naturally imposes higher demands on the process planning function. For example, a product with free form surfaces would be virtually impossible to prepare using manual NC programming, while it is a matter of mouse clicks to define the tool paths in 3D CAM software. A similar situation applies to the product material, where materials with lower machinability need specific tools and set-ups to be machined efficiently, thus making tool selection more intricate.

Environmental requirements are often considered to stand in opposition to cost reduction initiatives. However, the situation can be the opposite where no direct conflict between production efficiency and environmental consciousness regarding material recycling (Ståhl, 2007). Material recycling does not have a direct influence on process planning. Other factors however do, and today there are is an understanding for correlating objectives in lean production and environmental benign or green manufacturing (Bergmiller, 2006; Herrmann, Thiede et al., 2008). Raising customer awareness and initiatives to raise customer awareness for environmental issues (NN, 2008; NN, 2009a), puts pressure on all company operations to adopt more environmental conscious thinking. On the contrary, there is limited understanding from the industry to make environmental improvements in order to gain economical benefits (Kaebernick and Kara, 2006). The principal environmental impact from CNC machining concerns electrical energy consumption (Dahmus and Gutowski, 2004), both during machining, but also during standby.

As an example, the Volvo group has increased the energy consumption, but net sales have increased likewise, hence the ratio between energy consumption and net sales have decreased (NN, 2009b). Naturally the products from the Volvo group and alike have the main environmental impact during use, albeit the environmental impact from company operations cannot be neglected. As mentioned in chapter 1.1, it is in this case principally the component design that influences the environmental performance during the product lifecycle.

2.2 Internal constraints

The decisions that are taken throughout process planning most often influence subsequent steps and possible future decisions; internal constraints are introduced. This means that if constraints imposed earlier in process planning cannot be overcome - an earlier decision must be revised. Iteration of process planning activities is therefore often necessary. This is especially the case when planning for a new product and/or innovative machining, where process planning is exploratory.

The setup of the machine and machining parameters and results are closely interrelated. If one parameter is changed, the prerequisites for other parameters are changed as well. This has the consequence that the complexity level of process planning increases. To this adds that a part often can be machined in a multitude of ways. Which one of the machining strategies that are the correct one depends on company objectives (Figure 8). The objectives are however not the process planners' task to decide upon, which requirements and demands the machining process must fulfil, but rather a management issue (Halevi, 2003). Subsequent chapters will introduce the reader to some of the internal constraints. The reader will find some similarities in chapter 3.1. This is because the constraints to a great extent correspond to the process planning activities.

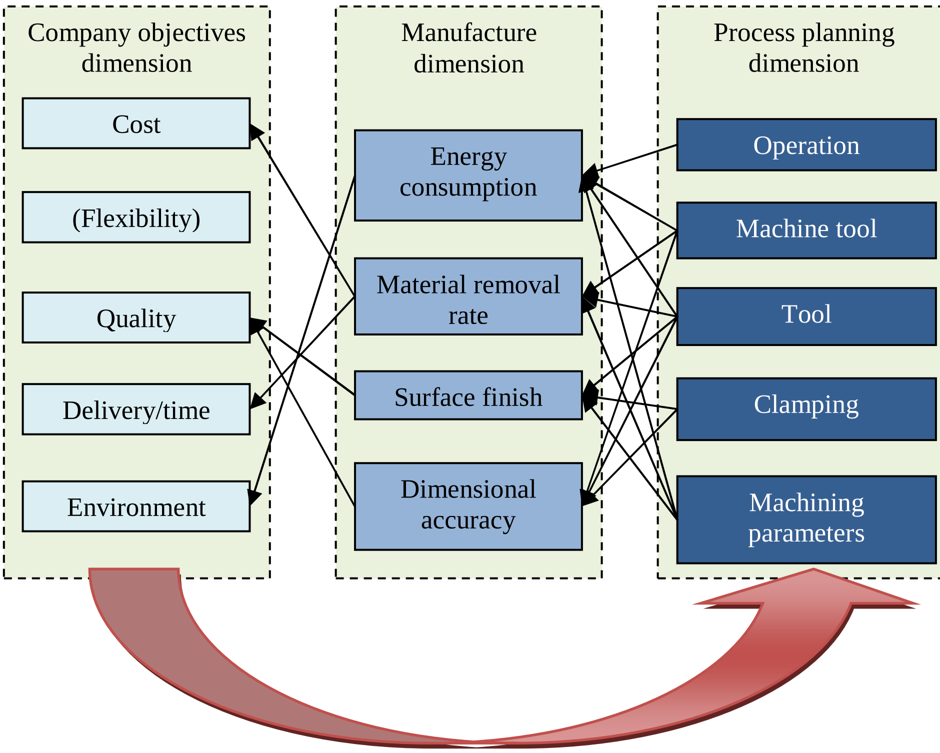


Figure 8. Relation between process planning and company objectives via manufacture dimension.

2.2.1 Machining operations

In many cases a part can be machined, not only by one type of operation, but there are often several alternative possibilities. Often optimisation algorithms focus on the cutting speed as the main optimisation parameter, but if the chosen operation is inferior to other operations, the process will never be globally optimised. It is therefore important to initially ensure that the most appropriate machining operation is selected. The process planner initially usually defines the required set of operations to produce the part. Principally any combination of turning, milling, drilling, and threading operations are possible. Each of the principle processes holds a variety of different operations. A rotational symmetric outer dimension can for example be machined trough turning or through rotational milling. An internal hole can be machined through boring or drilling, spherical milling or in some cases through internal turning. The decisions are therefore not always trivial or unambiguous. The selections influence the requirements on machine tool e.g. if one or several machine are needed, re-clamping, tool magazine size, tools in stock etc.

2.2.2 Machine tools

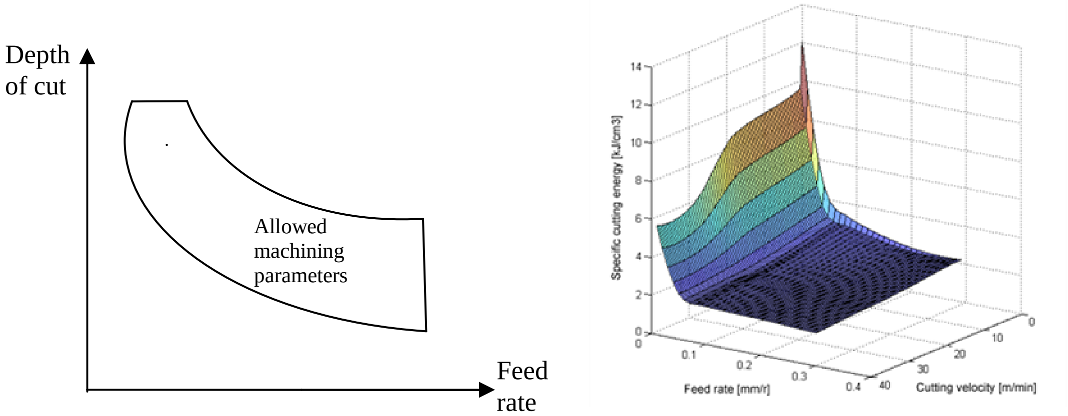
Different machine tools have different features regarding possible operations, axes, stability, rigidness, accuracy, power, spindle torque, work space, available speeds and feeds, number of tools, tool change times, hourly rate, batch quantity etc. (Halevi, 2003). The machine tool influence lead times, set-up times, machining costs, quality, tendency for vibrations, re-clamping, etc. Consequently the machine selection renders a set of constraints that the process planner must regard.

2.2.3 Cutting tools

The selection of cutting tool has great influence on the possible machining parameters. Tools come in different material, coatings, micro and macro geometry. Often cutting tools consist of two parts; insert and tool holder. The cutting tool has direct relation to surface finish and the power requirements, and forces on the tool/workpiece and thereby influence the tendency for vibrations. The main factors to consider in the tool selection are tool geometry (so that desired part geometry is generated), tool life and removal rate. It is of interest to minimize the number of different tools, since it limits the complexity and cost for stocks, ordering, but also reduces the set-up time and tool change over time. Deciding upon a cutting tool (insert and holder) is a fairly complex process, since the alternatives and combinations are almost endless. A comprehensive review of tool selection is however outside the scope of this thesis.

2.2.4 Machining parameters

All operations have the fundamental machining parameters - depth of cut, cutting velocity and feed rate. However, the meaning of them varies slightly according to the operation. The machining parameters can be regarded as the final optimisation of the machining process. Machining parameters have a huge influence on the machining process, by having a continuous and normally wide span of possible parameters combinations (Figure 9-a). The machining parameters directly correlate to material removal rate and consequently machining cost and time. Machining parameters are also tightly connected to tool life and the decision between material removal rate and tool life is the major optimisation to be made for a machining operation. Most optimisation algorithms for selecting economic cutting speed in relation to tool life are based on F.W. Taylor 1907 year’s equation. To this day, no one has suggested a better substitute, although it sometimes is extended with more parameters (Halevi, 2003). Machine power often acts as the upper limit for possible machining parameters, if tool life is not the limiting criterion. The machining parameters have a non-linear relation to specific cutting energy, which is the energy required to remove a volume unit of the material. This means that machining parameters influence the machining power and energy consumption, and can constitute a part in optimising machining operations for efficient use of energy.



a) b)

Figure 9. a) Allowed combinations of feed rate and depth of cut for an exemplified turning tool. b) Specific energy as a function of feed rate and cutting velocity in turning.

2.2.5 Workpiece positioning

It is necessary to decide upon a way of holding the workpiece in place to guarantee dimensional accuracy (i.e. tolerances). During machining large forces (e.g. gravity, cutting forces, rotational, vibrations) act on the workpiece. The fixture must accordingly ensure that the workpiece is held in place, and that it does not damage the workpiece. The clamping system has direct influence on the system rigidity and stiffness, and it is consequently important to ensure that the clamping gives enough stiffness so that optimal machining parameters can be used. More efficient machining (higher removal rate) also imposes higher forces on the workpiece and on the clamping. Clamping thereby has indirect influence on machining time/cost and quality. The workpiece fixture should not obstruct the tool travel operation. (Halevi and Weill, 1995) In the optimal case no re-clamping should be necessary in order to perform all machining operations. This reduces the likelihood for errors and geometric deviations related to workpiece positioning. To only use one work piece set-up also enables shorter manufacturing lead times, since re-clamping often must be done by machine operator. It is of advantage if standard fixtures can be used, since dedicated fixture design usually is costly and increases the time before manufacture commences.

2.2.6 Process planning and concurrent engineering

Concurrent engineering is an organisational approach to meet higher demands of shortened product realisation lead times. It implies a closer cooperation between different functional areas within a company. The major lead time improvement is not on the total time/resource consumption but on the compaction of the total time span. Concurrent Engineering not only has the potential of shortening the total lead time, but also to create better and cheaper products since the communication between disciplines that traditionally has been rather limited, is facilitated. This means that impossible or unnecessarily costly designs can be avoided at an earlier stage. The advancement of concurrent engineering has thereby put more pressure of the process planning function, since its interaction with other company functions increases in importance. Efficient transfer of data, information and knowledge increases in importance. The information transfer is becoming more complex with the size of the organisation, where product development, process planning and/or manufacturing unit may be geographically dispersed. PDM/PLM systems are in this perspective, important aids for transfer of information and coordination of product realisation activities.

3 Process planning

Process planning is an essential part of product realisation. The product realisation process comprises all the activities that are necessary in order to develop, manufacture and distribute a product to a customer. The chain always starts with an idea of some kind that must be transformed into a functional product concept through a design process. In order to be physically realisable, the design concept, along with requirements must be transformed into a process plan, which is implemented in the manufacturing system (Figure 10). The various product realisation activities can be performed internally or externally (out-sourced) in relation to the main manufacturer.

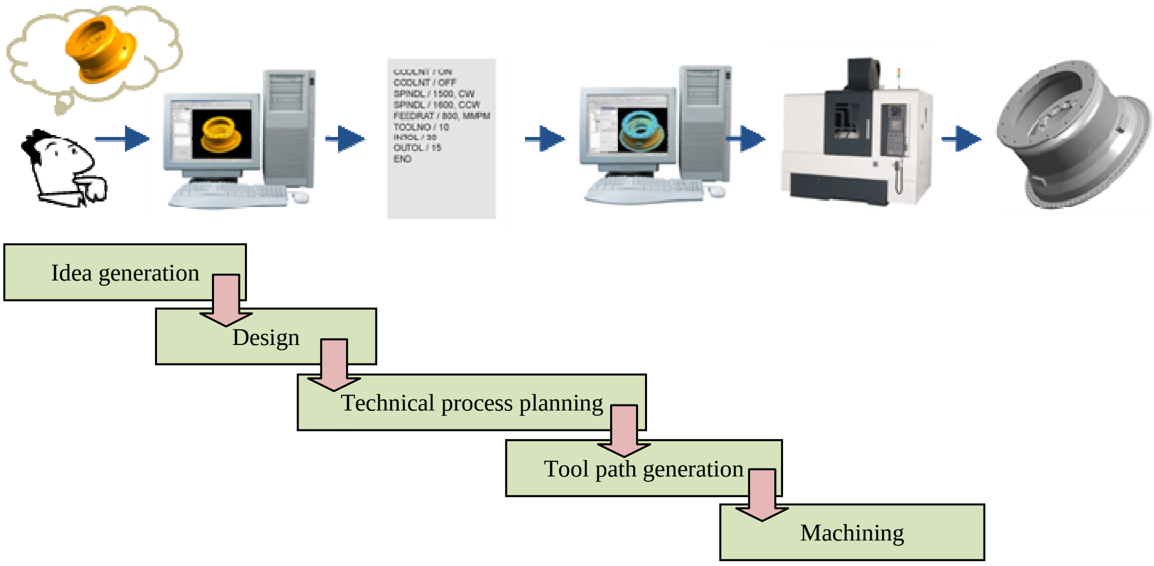


Figure 10. The principal product realisation flow chart using concurrent engineering. The arrows illustrate the constraints and requirements that each process generates.

In short one can say that process planning has the primary function to produce a process plan that unambiguously describes the complete manufacture of a product. A process plan for CNC machining typically includes the NC program as the centre piece and work instructions for operators and other staff concerned. Work instructions usually concern handling of workpiece, tool change intervals, quality control method etc. If the above stated are the results generated from process planning, process planning comprise the work activities that through a number of selections and decisions, transforms specifications and requirements into a process plan. The principal decisions concern selection of manufacturing process, machines, tools, workpiece holding, machining parameters etc. (Figure 11). Process planning work is in general labour intensive, highly subjective, time consuming and tedious (Wang and Li, 1991). The process planners' main work activities can roughly be regarded as being distributed as 15% technical decision making, 40% data, table reading/retrieval and calculations and 45% text and documentation (Halevi and Weill, 1995). In a value adding perspective it is primarily decision making that directly adds value to the final product, while the other are necessities for making capable decisions and producing a formal process plan. The aim of process planning improvements should consequently mainly be directed towards minimising the time and resources spent on non-value adding activities so that the resources can be freed for value adding activities (Figure 12). Process planning work requires personnel with good knowledge in e.g. manufacturing processes and shop floor practices. Due to the high reliance on humans and their knowledge/experience the produced process plans often lack consistency. A study showed that a sample of 425 relatively simple gears resulted in 377 different process plans (Wang and Li, 1991). This means that a process plan for a specific case (product, set of requirements), produced by two different process planners very seldom will be identical. However, this does not mean that there will be huge differences and the main machining process is probably similar, but selected operations, machining parameters may differ, which influence quality, cost and energy consumption parameters.

The activities both during process planning and product realisation can in general be carried out in a serial or concurrent flow of activities. A combination of the two is also possible. Concurrency between activities (as in Concurrent Engineering) is often preferred, since it reduces lead times and can increase e.g. quality of output. In this thesis, Concurrent Engineering is considered desirable and should take place during process planning, even if figures normally show serial flows due to simplification and readability reasons.

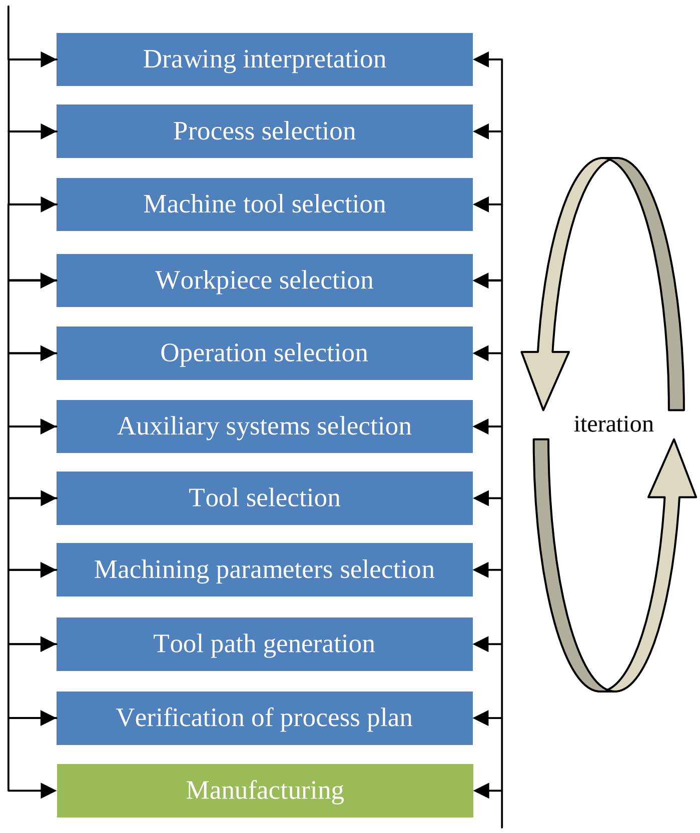


Figure 11. The main process planning activities.

Figure 12 illustrates the principal process planning function. Main value adding activities are decision making activities (i.e. concept generation and concept decisions), which available time and resources should be focused on, whereas the resource need for other activities should be minimised. In this perspective, data/information/knowledge retrieval and classification, which are inputs to the process planner, should be automated to minimise the need for human interaction and resources spent. Similarly, to generate a formalised process planning output, once the process has been defined, is also an activity that should be minimised regarding resource use. The main activities herein are NC programming and work instructions generation, which to a great extent is clerical work, thus fit for automation. To minimise the time for the described non-value adding activities implies that more resources can be dedicated to decisions (as stated in Figure 11) and optimisations that influence the effectiveness of process planning (i.e. machining process and the product). In relation to Ref. (Halevi and Weill, 1995) observations of resource use for different process planning work, only 15% of the resources go into direct value adding activities. In Figure 12 this corresponds to concept generation and concept decisions. The bulk of the process planning resources are dedicated to information management, calculations and generation of the process plan. Better process planning efficiency can be achieved with more efficient process planning aids, as for example IT systems, PLM systems, CAM but also through better and more systematic working methods. This will be further discussed in subsequent sections of the thesis.

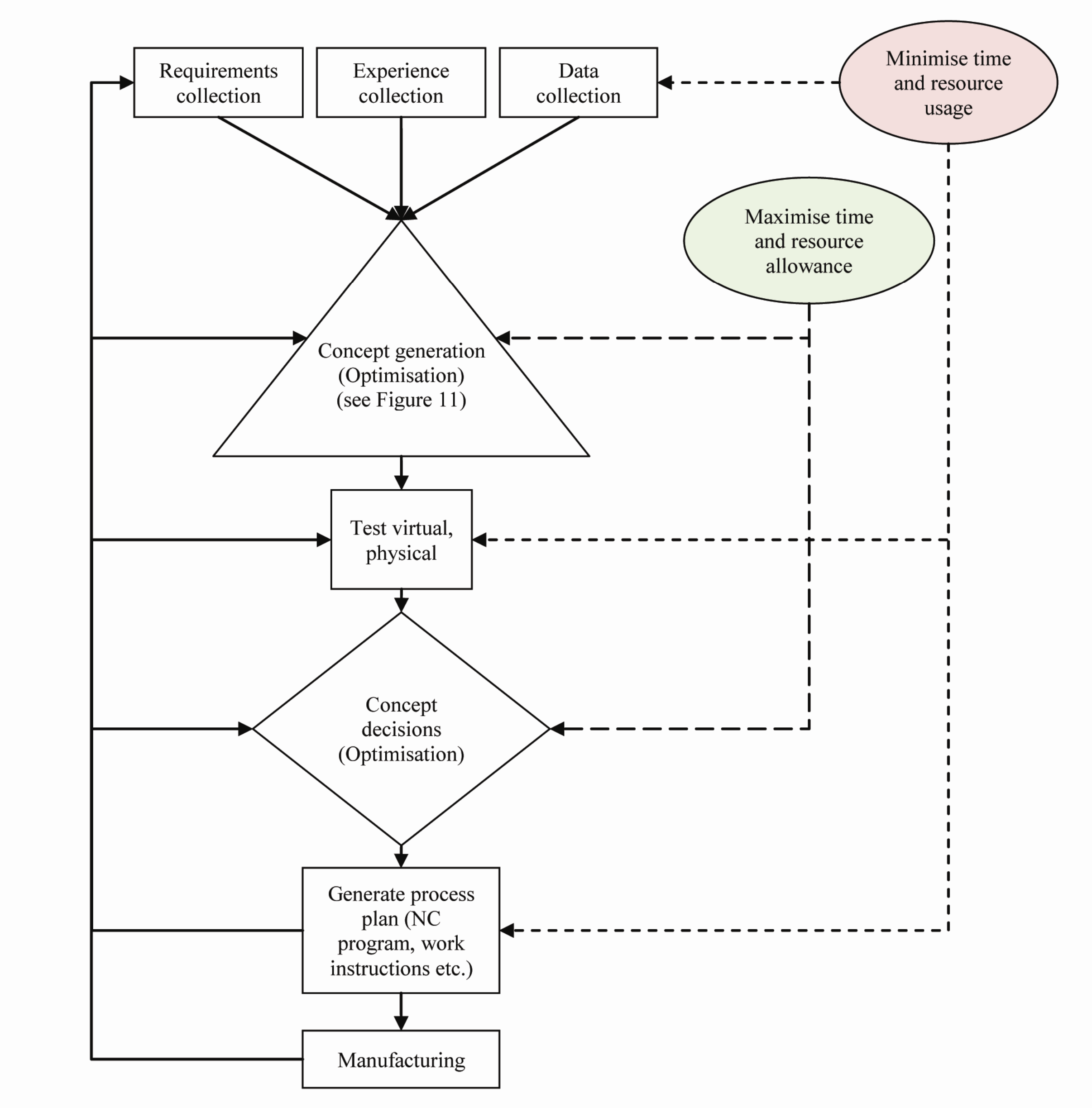


Figure 12. Principal flow chart of process planning, iteration steps and distribution of resource usage priorities.

3.1 Principal process planning activities

Process planning is an important part of the production system, since it in detail defines the manufacturing process that transforms raw material into intended product. A great part of process planning consists of making selections and decisions between various options and parameters. The principal activities of process planning are illustrated in Figure 11 and described hereunder:

- *Interpretation of technical drawing* - a thorough analysis of the drawing must be carried out before the actual planning commences. The planner must regard materials, dimensions, tolerances, surfaces finishes, how quality measures and verification of manufactured can be carried out etc.
- *Processes and operations selection* - the production planner must initially make decisions of the production techniques (casting, machining, welding, forging etc.) to employ. When this is done, the process planner makes a decision of the operations and their sequence. The selection of processes and operations are made in accordance to the constraints in connection to the product, manufacturing system and its environment etc. as described in chapter 2.
- *Machine tool selection* - the selection of the appropriate machine according to operations, availability, size and power etc.
- *Workpiece selection* - the freedom of deciding upon different workpiece types depends on the production batch size. For short series production most certainly a standard off the shelf workpiece is used, which means that a lot of material may have to be removed. With increasing production batch sizes a more near net shape workpiece is profitable. This means that less material must be removed, hence a shorter machining process. It is also more environmentally beneficial, since less material is casted, transported and removed. Utterly it is a matter of trade off between casting (workpiece) cost versus machining cost.
- *Fixture selection* - the selection of workpiece positioning method is partly a matter of operations, direction of operations, number of pieces to machine in one setup and features of the machined part. Sometimes the clamping of the machine tool can be used, whereas at other times a tombstone or a dedicatedly designed fixture must be used.
- *Auxiliary system selection* – in many cases the machine tool work in accordance to other systems in the manufacturing system. It can be flood cooling or Minimal Quantity Lubrication (MQL) systems, or automation systems such as robots etc. The process planner must consequently make decisions regarding the usage of available auxiliary systems. When it comes to the cooling of the cutting process, it is an area where currently a lot of research is undertaken. This is because traditional methods such as flood cooling have negative influence on the working environment and the environment in general. It is also linked to a large cost in many cases, and can account for a larger cost than tooling (Astakhov, 2008).
- *Tool selection* - the selection of cutting tools (tool holder and inserts etc.) largely influence machining cost and time. There is a huge range of possible combinations of tool vendors, materials, grades, coatings, micro/macro geometry of cutting tools, which make optimal decisions difficult. (See chapter 3.5) Tool selection stand in close relation to possible machining parameters.

- *Machining parameters selection* - the influence of machining parameters stand in direct relation to machining cost and time, thus the profitability of operations. It also influence on the energy consumption of the machining operations, which means that it can contribute to a more energy efficient manufacturing system if parameters are properly set. The cutting speed is often the parameter that optimises the operations as used in Taylor's formula of economic cutting speed. However, feed rate and depth are cut important to regard since they show a non-linear relation with the specific cutting energy and by selecting the machining parameters wisely a lower specific cutting energy can be achieved, which leads to better circumstances for the tool, but also to decreased total electrical consumption. (See chapter 3.5)
- *Tool path generation* - It is often done in CAM or by manual offline or online NC programming and defines the moves of the tools over the workpiece. (See chapter 3.6)
- *Verification of process plan* - The above made decisions fulfilment of process demands must be verified in some way. Sometimes actual machining is the sole testing, but often some sort of simulation is carried out to avoid problems at an early stage. Simulation can be carried out in CAM, stand-alone software or in the control panel on the machine and can have different scope. In some cases, only geometrical accuracy is verified, sometimes collision occurrences are verified. A process is always subject to variations where simulation of tool paths and collisions etc. do not provide information on the continuous performance of the machining process. Decisions on process plan verification in a manufacturing situation must be consequently evaluated. It can include various statistical methods for quality control of the resulting components, e.g. Statistical Process Control (SPC) (Halevi, 2003). Chapter 3.1.1 discusses verification requirements in relation to data levels.
- To the general process planning activities adds the creation of work instructions for machine operators, which is part of the process planner's work as well. (See chapter 3.8)

The decision order has importance, since a decision also includes constraints (chapter 2.2 presented the internal constraints on process planning) on the subsequent activities in the planning process. The selection of machine is one example of this, constraints the possible operations in one clamping and the machining parameters, since every machine has a maximum power, spindle speed, possible operations, number of manipulation axes etc. This is one of the reasons why iterations are frequent during process planning. Sometimes a prior decision restricts subsequent decisions in such a manner that specifications cannot be met. Consequently iteration is necessary. Iterations can be regarded as reactions of errors, since they are necessary in order to reach a better solution. Iterations prolong the process planning lead time and to increase process planning efficiency, a reduction of the need for iterations is desired. It in this context desired to make right decisions the first time. Another option is to reduce the time required for making an iteration step. In this perspective, simulations can be efficient tools. As mentioned previously, concurrency between activities can occur, which means that the above list of activities should not be regarded as a strict sequence of actions, but they are still interrelated.

The traditional approach towards process planning has been to build a process plan from scratch, for each part that is being manufactured. This approach requires substantial retrieval and manipulation of information from many different sources (Denkena, Shpitalni et al., 2007). Figure 13 illustrates a possible distinction between different automation levels in process planning. Process planning invigorate as mentioned, many different areas, which can be subjected to automation. Figure 13 simplifies a multi-dimensional situation.

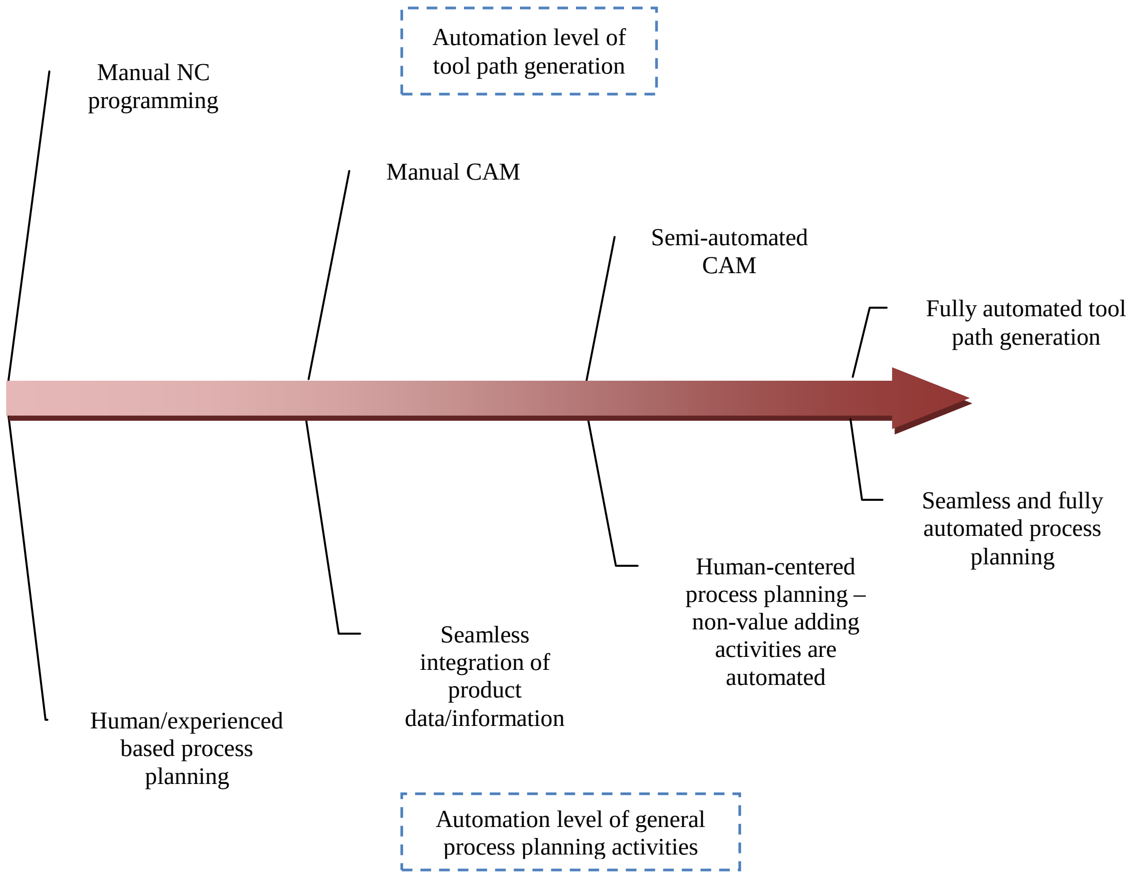


Figure 13. Automation level scale of process planning

3.1.1 Data levels

In general there are three different levels of data (see Figure 14) in respect to the reliability of the machining process outcome. If machining parameters for a certain operation, tool and workpiece material are regarded, data of the first level gives a fairly wide window for machining parameter selection as found in general machining handbooks and tool vendor catalogues. This renders a situation where the outcome can vary more, thus the reliability of the outcome is low. The second level refer to more specific data where published industrial experiences or scientific papers provide a narrowed down process window for the current machining case. This renders higher reliability of output in respect to aforementioned more general level of data. The third and highest level of data refer to data that are extracted from own tests under the specific circumstances of interest or data retrieved from former manufacturing processes under identical circumstances. The type of available process planning data influences the safety margin in the machining processes. If data is reliable, less safety margins are required, which will lead to more robust and efficient machining processes.

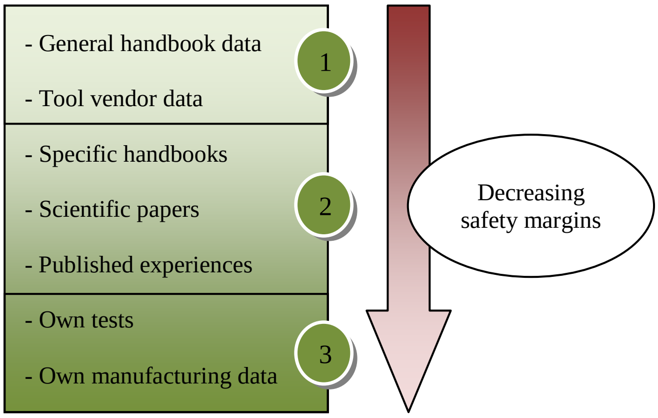


Figure 14. Relation between data level and necessary safety margins during machining.

In analogy to aforementioned, Figure 15 illustrates the difference between established, new and innovative processes in a process planning perspective for validation. An established process may not require any validation since from own experience, the process planner is ensured that the selected process will work. However, depending on the innovativeness of a process, certain aids must be employed to validate the process. Simulations and physical machining are examples of such aids. Since physical machining typically are connected with higher costs, simulations are preferred. However, if simulations (due to lacks in models, process knowledge, algorithms etc.) do not provide reliable output data, physical machining is necessary.

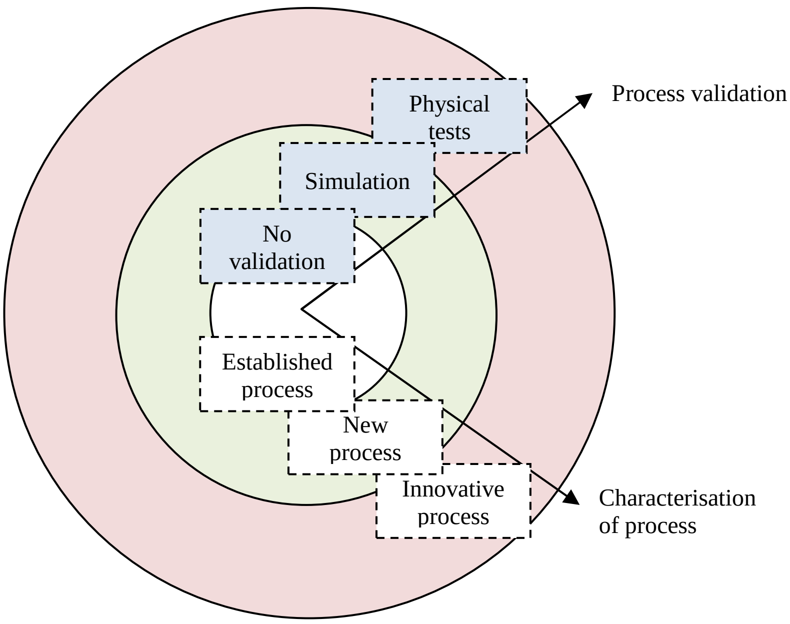


Figure 15. Depending on how established the process is, certain measures for process validation are required.

3.2 Optimisation

Since process planning comprises many decisions and formal/informal optimisations - optimisation is dedicated a chapter. In general, the purpose of the optimisation process is to determine a system so that the specified goals and objectives are most nearly achieved (Meredith, Wong et al., 1973). In any system, there exist a set of different concepts that fulfil specified goals, objectives and criteria in different ways (Table 1). It is therefore important that the company have specified goals that can be related to, so that the system is optimized according to the actual goals. Optimisation of parameters and demands and requirements is the centre point of process planning, since decisions and selections should generate an optimal process plan. A process planning function that can provide better decisions is therefore the aim of improvements and it imposes requirements of the design of the process planning function and its relation to other company functions.

Table 1. Relation between goals, objectives and criteria (Meredith, Wong et al., 1973)

Goals	Objectives	Criteria
Maximise profit from investment	1) Minimize cost 2) Maximise income	Capital investment in dollars, operational cost, maintenance cost, interest cost, city taxes, rental rates, occupancy rate, tenant's income levels

The optimum solution is usually defined as the technically best solution that is achieved without any trade-off between goals and objectives. Since the goals, objectives and criteria inevitable conflict, the engineer or process planner must make trade-offs in the optimisation process. (Meredith, Wong et al., 1973) Three principal types of optimisation methods: Analytical, combinatorial and subjective. Process planning characterised by major parts of human interaction leans heavily to the subjective form of optimisation, where the optimisation is taking place in the head of the process planner.

The simpler form of process planning occurs when machine tool, cutting tools, fixture and product specifications are given. It is then an issue of using the given constraints and to use them in an optimal way in accordance to requirements and demands (Grieves, 2006). When any of the above constraints are open for modifications, as when new tools can be used, investment of new machine tool, new fixture development or changing of product specifications, then the complexity level of process planning consequently will increase. However, the possible permutations, thus the complexity level of parameter optimisation in the simpler case is high, which means that only a subset of the possible permutations is evaluated. Usually the search for a solution of the given problem is aborted when a combination of parameters satisfy the given requirements. (Grieves, 2006) Human beings are not well equipped in performing those searches and optimisations. However, this is often the case - that information and data retrieval alongside the combination of it into concepts are highly manual work. As the following chapters show, there are various computer aids and methods that aids the process planner during decision making in order to produce more optimal solutions and consistent process plans.

3.3 Process planning methodology

The following chapters present the principal different ways of conducting process planning work. It can essentially be categorised under two categories; human-based and Computer-Based Process Planning (CAPP). The latter concept refers to a wide span regarding the automation level of fully automated and semi-automated process planning systems.

3.4 Human-based process planning

Human-based or experienced-based process planning is still common in many companies. It is to the major part based on manual work activities. The process planner in these systems base decisions on knowledge from many different sources, e.g. experience, handbooks, tool manufacturers' data sheets etc. This also implicates that it is the responsibility of the process planner to retrieve applicable information. The decisions made are often subjective in nature and due to the large quantity of information and data available does not necessarily generate the optimal concept or solution to the problem. A process planner in these situations must possess the following characteristics to be able to prepare a process plan (Chang, Wysk et al., 1998):

- Ability to read engineering drawings (or solid models);
- Familiarity with manufacturing processes and practice;
- Familiarity with tooling and fixtures;
- Familiarity with raw materials;
- Know the available resources in the shop;
- Know how to use reference books, e.g. machinist handbooks;
- Ability to perform computations on machining time and cost;
- Know the relative/approximate costs of processes, tooling and raw materials.

As the reader realises, the above knowledge naturally correlates with many of the process planning steps as described above (chapter 3.1). Knowledge and experience are typically drawn from a wide range of sources during process planning. The knowledge can be categorized into four different types, depending on which area of the process planning activity they concern (Jia, Zhang et al., 2008):

- Handbook knowledge, which include e.g. tolerances, material, machining data and process planning specification as found in handbooks, brochures and standards;
- Manufacturing resource knowledge, which is data and knowledge connected to the manufacturing environment where the process planning takes place, e.g. machine, cutter, fixture and process planning database;
- Decision making knowledge is built up of experience, procedure algorithm and control knowledge in process planning;
- Model knowledge includes process planning data/knowledge model, e.g. information about product, operation, fixture, machine etc.

Human-based process planning as described above retrieve knowledge from various sources as illustrated in Figure 16.

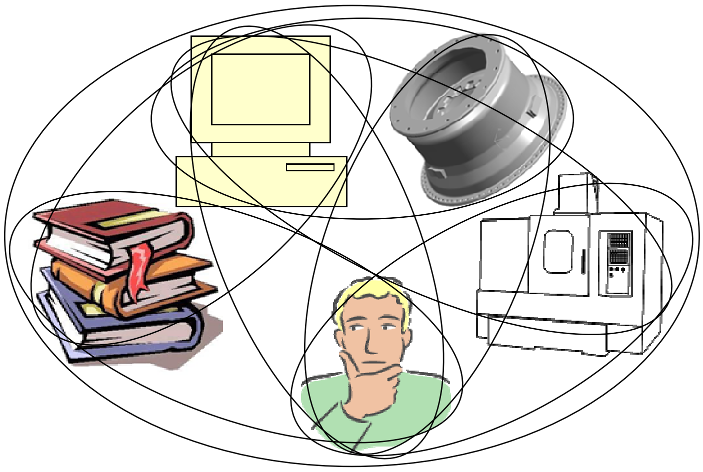


Figure 16. Experience-handbook-database-plant/process knowledge

A great part of the information regarding tool and machining parameter selection is taken from handbooks and tool manufacturer's data sheets and recommendations. A handbook is one way of formalising knowledge, which has long been a manufacturing practice. Process-capabilities are often represented in tables, graphs, figures, or listed as guidelines. Larger enterprises often have internal handbooks. Handbooks can serve as guide and reference (Chang, Wysk et al., 1998). Some machining organisations issue their own machining handbooks and machinability databases. The data presented herein usually provide starting values and the recommendations are sourced from many industries and technical literature (Halevi, 2003). Tool manufacturers also issue large amounts of recommendations for machining parameter settings. The data provided is often given for each tool individually. Traditionally the data was presented in catalogues, but nowadays many tool vendors have online interactive machining parameter selection – where the user define material, surface finish, cutting angles etc. and are given recommendations. Tool vendor data must often be handled with care (Halevi, 2003). Tool vendors can also have more direct interaction with customers, through visits and direct communication. It is not unusual that a tool vendor give direct recommendations for a specific machining situation regarding tool and machining parameter selection. In some cases a company can invite a number of tool vendors that will give recommendations on tooling and machining parameters. The customer then picks the tool vendor that fulfils the requirements the better.

Process planners obtain their experience from earlier training as machinists, from books or through discussions with colleagues. There are a number of inherent problems related to a process planning function that to the major part relies on the process planners' experience:

- Experience requires a significant acquisition period (Chang, Wysk et al., 1998);
- Experience only represent approximate, not exact knowledge (Chang, Wysk et al., 1998);
- Experience is not directly applicable to new processes or systems (Chang, Wysk et al., 1998);
- Experience is connected to individual persons, which make the organisation dependent on the knowledge of a few. If one leaves, also the knowledge leaves with him.

These factors with humans confine some of the important reasons, alongside the mentioned problems regarding information management and optimisation, for the development of computer-aided process planning systems.

3.5 Computer-aided process planning (CAPP)

Computer-Aided Process planning (CAPP) is the application where computers are used in order to assist or replace humans in order to produce better process plans during less time. The CAPP concept stands for a wide span regarding process planning automation. In its lowest form it will reduce the time and effort for process planning and provide more consistent process plans. In its highest form it will produce optimal process plans without human interference from a required set of inputs, i.e. the automated interface between design (CAD) and manufacturing (CAM) (Figure 17). (Wang and Li, 1991) There are a number of possible computer centred aids for process planning, which all have their different area of application and which dictate the type, quality and amount of information and data. Virtual tools have different characteristics regarding scope, when in the process (planning) flow they are applicable and the of data required (Grieves, 2006). CAPP has a long history, starting in the mid 1960s. Throughout its history different areas have been of interest, where the CAPP systems developed during the first 30 years were based on the variant approach (see chapter 3.5.1). Later CAPP systems were based on artificial intelligence technology and on generative or semi-generative methods. Until the mid 1990s some 300 scientific papers were published in the CAPP field. (Marri, Gunasekaran et al., 1998) During the 1970s initiatives in Sweden were taking in the area of CAPP. Master theses and papers were written in the field and a CAPP system, PRAUTO was developed during this time. (Kinnander, 2009) Despite the long history of development of CAPP systems, their usage is rather limited when it comes to the industry. This is particularly the case for SMEs (Denkena, Shpitalni et al., 2007).

Figure 17. Relation between CAD/CAPP/CAM

As discussed in previous chapters, process planning work is fundamentally a sequence of decisions. It is therefore appropriate to include a section that incorporates decision aids. The decisions that traditionally have been made by humans are made or aided by the CAPP system. Depending on the lead time and whether decisions are repeated or unique, different aids are more appropriate. Table 2 shows how various decisions aids are suitable for different situations. The presented decision aids only regard the efficiency of the immediate process (i.e. process planning), not the effectiveness. Despite this, Table 2 provides an understanding for applicable decision aids, where many process planners in many cases act by experience (intuition). A CAPP system act in the rule-based system field, by providing the process planner with rule-based decision aids (bootstrapping, simulations and information systems).

Table 2. Decision aids (Slovic, 1982)

Long lead time: Decision analysis	**Rule-based systems:** Bootstrapping Multiattribute utilities Computer information systems Simulation
Short lead time: Educated intuition	

Early attempts of automating process planning work with the aid of computers, primarily consisted of building computer assisted systems for report generation, storage and retrieval of process plans. Systems like these can save up to 40% of a process planner's time. Despite that they do not perform the actual process planning tasks, but merely reduces the amount of clerical work. (Chang, Wysk et al., 1998) Later developments of CAPP have been directed towards eliminating the process planner from the entire planning function. Some of the benefits this is expected to lead to include:

- Reduced need for skilled planners (Chang, Wysk et al., 1998)
- Reduced process planning time (Chang, Wysk et al., 1998)
- Reduced process planning and manufacturing costs (Chang, Wysk et al., 1998)
- Rationalisation and standardisation of process since more logical and consistent process plans are generated. (Groover, 2008)
- Productivity increase of process planners since more systematic work permit more work to be accomplished. (Groover, 2008)
- Improved legibility since computer-produced instructions are easier to read. (Groover, 2008)
- Incorporation of other application programs, such as cost estimation and work standards. (Groover, 2008)

Altogether, the above benefits of CAPP will lead to increased overall productivity of process planning (Chang, Wysk et al., 1998)

3.5.1 Fundamentals of CAPP systems

Although there are multiple choices to be made for machining operations for machining a part, CAPP systems only delivers one process plan (Marri, Gunasekaran et al., 1998). The different choices include multiple machine tools, machining sequences, machining parameters, tools etc. Principally there are four main elements in a CAPP system; input, output, database and manufacturing decision making rules (Marri, Gunasekaran et al., 1998), which also are the basic elements of human-based process planning. There exist a number of variations of CAPP, where a common discrimination of CAPP systems is whether it is based on the *variant* or the *generative* method. The exact meaning of each concept is not presented in this thesis, but is discussed in more depth by Ref: (Wang and Li, 1991; Halevi and Weill, 1995; Groover, 2008; Bagge, 2009). However, in short the generative method is more automatic and advanced in its process planning algorithm than the variant method, and is regarded as fully automatic process planning. The input is a text or graphic file and the software generates a process plan. It is a difficult and complex method due to extensive need of algorithms, decision logics and data in order to replace the human process planner and consequently difficult to develop for industrial implementation (Bagge, 2009). It is in this light not surprising that much of the process planning work still is performed by human beings. Inherent problems with CAPP systems are that they are restricted to interpolation of data rather than extrapolation. In respect to optimisation of machining parameters, this certainly leads to that robust parameters are selected, but for pushing the edge of new machining strategies and innovative machining, this is restricted.

To be able to implement a CAPP system, where the bulk of the process planning activities are automated, an assessment of the interface between neighbouring functions should be carried out. The central issue of the assessment is to investigate the input of information and data to the process planning function, whether this is compatible with the current system. If not, some sort of translation system must be employed (Ciambrone, 2008) to ensure that the CAPP system input is standardised and readable. This is especially important for suppliers that have a large changing customer base, which all employ different drawing standards, conventions and file formats. Not all customers may use CAD-models. Some use paper drawings, sketches or verbal methods to communicate part shape and requirements. Process planning input is heterogeneous in its nature. It can under these circumstances be difficult to easily use a CAPP system without human interaction (Figure 18).

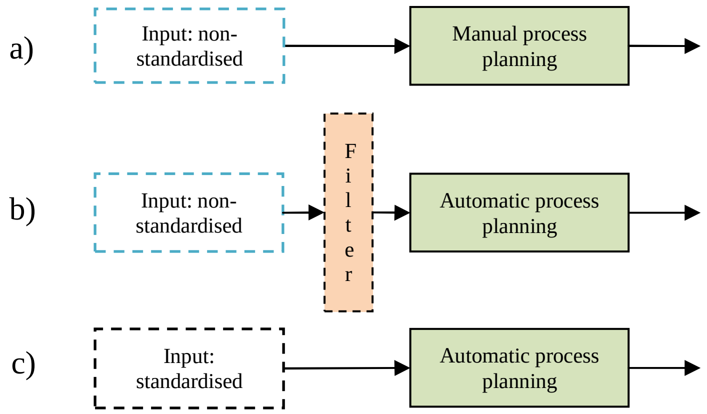


Figure 18. Different approaches to overcome problems with input heterogeneity.

3.6 Tool path generation

NC programs are not seldom created by the NC programmer from a 2D blue print of the part. The result can spread due to the proficiency level of the NC programmer and how geometric features are interpreted etc. This is one of the reasons for automating the tool path generation, which prompted the development of CAM. (Wang, 1987) However, the benefits of CAM, it is still common in the metal working industry to use manual NC programming, in some cases for certain products and operations that are performed on certain machine tools or simple products and in some cases for all produced products.

There are two driving mechanisms behind the automation of tool path generation/CAM. The first is increased quality, by closing the interpretational/communication gap between product design and process planning, where uncertainties may and will result in faulty parts that does not meet customer demands. Second the product realization lead time is a factor that is reduced when labour intense manual programming work is automated. In total, this will have positive impacts on the cost of the product realisation process and thus the profitability of the company. Already from the beginning of the NC machine history, it was realised that manual programming of tool paths would be too tedious (Chang and Joshi, 2001). Even for simple geometries the programming is rather complex. Tool offsets must be calculated using trigonometry, which means that even for rather simple parts the computational work can be cumbersome. For complex shapes and increasing number of machine axes (e.g. 5-axis machining), it is virtually impossible to perform manual NC programming. There are many potential error sources in manual NC programming. This was the starting point of CAM development and APT (Automatic Programmed Tooling) was the first outcome (Chang and Joshi, 2001). APT is a program language the lets the programmer define machining parameters and tool path. CAM developed from APT, by replacing the program code and enabling programming through a graphical interface (Machover, 1996). By using CAM, where the tool paths are generated directly on the CAD model, the risk for measure interpretation errors and miscalculations are eliminated.

Still today, problems exist in the integration between the product design phase and the process planning phase. The issue has a long history but yet there is no generic solution that all companies use. Even with the use of CAD and CAM systems, which corresponds to the above company functions, most companies use CAD systems today, while CAM, although common is not as frequently employed. This means that it is virtually impossible to have a seamless integration between the design and the process planning phase. A process planning system that is integrated with the CAD/CAM system have the potential to transfer information and data about geometry, tolerances (dimensional, geometric and surface finish), material type, special customer requirements, batch size and part number. This information typically have different creators and sources, where e.g. geometric data may come from the CAD system whereas all other information would come from other sources, e.g. manufacturing databases or the user. (Husbands, Mill et al., 1987) In relation to CAPP, CAM preparation mainly concerns the generation of tool paths, whereas CAPP includes many more of the process planning activities (chapter 3.5). The outcome from the CAM software is a part that meets dimensional requirements (at least theoretically).

3.7 Simulation

Most CAM software allow simulations of the NC program. The simulations carried out in CAM mostly concern verification of tool paths. This means that it is principally the tool moves during cutting that is simulated and the result is that the programmer can verify that the correct geometries are generated with selected tools. In addition to this simulation, there are two more possible simulations to verify that the produced part fulfils defined requirements.

Collision simulation: The post processed NC program is tested in a virtual environment that must consist of 3D solid models of machine tool, cutting tools, machined part, raw part geometry and fixtures to verify that no collision between tools and part, fixtures and machine occur with the defined set of tool paths. Collision simulation is an efficient method for 3-axis machining, but it is indispensible in 5-axis machining (Lopez De Lacalle, Lamikiz et al., 2005). The reason why simulation increases in importance for machines with increasing number of axis, is that axes interpolation is more complex and thereby making collision predictability more difficult (Lopez De Lacalle, Lamikiz et al., 2005). Simulation software are often used as plug-in software to the CAM system, although some CAM systems have integrated collision testing (Lopez De Lacalle, Lamikiz et al., 2005). However, collision simulation does not guarantee a problem free machining process, since it only includes geometric information. It is in this perspective interesting to investigate the need for machining process simulations.

Machining dynamics simulation: The simulations provided in CAM software are static and deterministic (the same result for each simulation). Even if CNC machining is a fully automated process, it still depends on a number of dynamic parameters that in some cases are crucial for the result, in other of minor importance. The physical machining is complex, since physical properties are introduced, e.g. work piece material, tool material, tool wear, machine dynamics etc., which can influence the robustness of the machining process, economics, and quality of produced parts.

By using virtual tools instead of testing the NC program in a physical setup, using plastic or wood models, much time can be saved. This is important in a Concurrent Engineering perspective. Not only is it time consuming, it can also impose danger to the operator to machine an errant NC program. (Xiao, Han et al., 1996) The use of simulations enhances the need of data connected to process planning. Without good models of the simulated system, no reliable results can be expected.

3.8 Automated work instruction production

In most companies a work instruction for the machine operator must be developed for each product/NC program and is usually part of the process plan. This instruction can be digital or analogue. The instructions are written for the machine tool operator's guidance in loading/unloading the machine, tool changes, quality testing, machine surveillance etc. The instructions are often written manually by the process planner and in most cases very little standardisation of language and terms are used, meaning that within a company and between process planners the work instructions can have different presentations. To use standardised terminology in work instruction, not only benefits the machine operators, it also enables more efficient information management in databases, where standardised phrases can be reused. The production of work instructions can also be regarded as non-value adding activities, since it typically does not contribute to the machining process itself and no optimisation and decisions are made, merely clerical work. Work instruction production is obviously an activity subjected for automation.

3.9 Product Lifecycle Management systems

Product Lifecycle Management - PLM (and sometimes referred to as Product Data Management - PDM) does not have a singular definition, but several and an absolute definition is outside the scope of this thesis. However a PLM system work as an aid in the management of products processes and services from initial concept through design, engineering, manufacture and end of life (Ming, Yan et al., 2007). It can therefore be a vital part of the process planning function, which is a large consumer of data and information. A CAD model only contains a fraction of the total information that is created during product development. Different functions in the organisation uses different information, but often some information must be shared (Walsh and Cormier, 2006). There is hereby a need for collecting all information connected to a product to be more easily available for all who needs it. PLM has rather recently been recognised as business model to aid the integration between people, process and technology in companies (Ming, Yan et al., 2007). Most commercial PDM/PLM systems contains the following functionality (Walsh and Cormier, 2006):

- Management of data consistency to guarantee that revisions of products are executed throughout the system and linked data;
- Prevention of unauthorised changes of data;
- Management of revision and change histories;
- Control of users so that users not simultaneously attempts modification of data.

Since PLM systems are cross functional, they must have an interface with all the used aids in order to guarantee efficient information and data management. With increased IT usage, computer software, the demand and drive for standardised representation of information and data increases. This has implications for the whole organisation regarding implementation of e.g. simulation software; that data and information is available and can be retrieved efficiently. The benefit of having model based information is that if input specifications change during the product realisation, the entire planning process must be repeated (Kulon, Broomhead et al., 2006). These days geometric information is managed through CAD models and IT systems, while other information from catalogues, database, and engineering standards must be managed separately without integrated tools (Kulon, Broomhead et al., 2006). This is one of the main drawbacks of using handbooks and other non-interactive and product based information. However, Ref (Pejryd and Andersson, 2006) showed that a complete solution of a PLM and Enterprise Resource Planning (ERP) system virtually can manage all types of information.

3.10 Knowledge-Based Engineering

In common with many other concepts, Knowledge-Based Engineering (KBE) lacks a standard definition and consequently many competing definitions of KBE exist. Ref (Tsoukalas, 2007) defines a KBE system as *an intelligent computer program that uses rule-based knowledge and interference procedures to solve problems that are difficult and require significant human expertise for their solutions*. This definition solely focuses on the use of knowledge for producing better decisions. Other definitions focuses on the reuse and capture of product and process knowledge (Stokes, 2001). The foundation of KBE is however the aim of using knowledge in a more systematic way in order to produce better decisions in engineering processes. An initial approach to process planning automating can be to free the process planner from unnecessary repetitive work tasks such as clerical work and repetitive calculations so that more time can be dedicated to creative work (Kulon, Broomhead et al., 2006). A Knowledge-Based Engineering (KBE) system leads the user through the process (Kulon, Broomhead et al., 2006). The benefit of reusing parts or wholes of formerly defined processes is that those processes already have been tested in a real manufacturing setting (see chapter 3.1.1). Duplication of mistakes are kept to a minimum and energy and time spent on duplicating already used process activities can be used for process improvements, i.e. allowing more time for decision makings. (Grieves, 2006)

Personal productivity depends partly on the availability to receive, process and act on information (Kinsky, 1994). When knowledge and information is discussed, it is appropriate to include a list of different types of information. When developing the process planning function, it is important to distinguish between different types of information, since they must be treated differently. Information can be distinguished as follows (Kinsky, 1994):

- *Internal information*, such as operating procedures, product information and strategies.
- *External information*, e.g. information about competitors, sub-suppliers, vendors and customers, technological development.
- *Degradable information:* Information that is not stored in a permanent form, such as information received through human senses.
- *Non-degradable information:* Information stored permanently, e.g. on paper or disk.
- *Structured information:* Information that is produced in a structured form on a planned basis and often created by an information system.
- *Unstructured information:* Information not received in a structured form or on a planned basis, often transmitted by human communication.

Information with high quality to the business function or operation should meet four requirements on; relevance, timeliness, completeness and reliability (accuracy and authenticity) (Kinsky, 1994). These requirements are also fundamental for process planning and it imposes demands on the management of information.

3.11 Dimensions and measurement of performance

The old devise reads ‘one cannot improve what one cannot measure’, which implies that individual process activities need to be measured in order to be managed and improved. Figure 19 illustrates how performance measurements can benefit the business and company objectives and goals in a continuous improvement program, where one set of performance measures and metrics are valid for a certain place in time and accordingly adapted to the advancements made. When discussing performance measurements, it also essential to define to fundamental parts of the measurement system. As mentioned a differentiation is made between a measure and a metric according to the IEEE standard glossary:

- A *measure* is a standard, unit, or result from a measurement (NN, 1983);
- A *metric* is a quantitative measure of the degree to which a system, entity, or process possesses a given attribute (NN, 1990).

A measure without a metric or a value to compare the measure against is not worth anything if meaningful decisions are to be made from the measures (Kankanhalli and Tan, 2004). Performance measures should be defined according to the company strategy – goals and objectives (Bond, 1999). When measuring an organisation, system or a process it is important to establish the appropriate performance indicator(s). Many of the performance indicators are not subject to a standardised definition, but several, which is especially the case for productivity (Tangen, 2007; Murgau, 2009). The lack of coherent definitions of performance indicators makes it difficult to unambiguously communicate performance to involved parties. This thesis will not discuss performance measures in depth, but since performance is central in this thesis, a few of the most common indicators are shortly presented and reviewed hereunder:

- *Effectiveness*: Effectiveness is a measure of the achievement of a number of objectives that maximises the overall benefit of the company (Kinsky, 1994) in other words the ability to get the right things done at the right time, e.g. establishing the right quality level that meet customer requirements;

- *Efficiency*: The quality or degree of effective operations as measured against cost, resources, and time. (NN, 1995);
- *Productivity*: Productivity is often defined as the value added by the process divided by the value of the labour and capital consumed. (NN, 1995), however many alternative definitions exists as stated above;
- *Quality*: The degree to which a service or product meet customer requirements. (NN, 1995);
- *Timeliness*: The ability to perform company activities on agreed time. (NN, 1995);
- *Value:* The function divided by the resources used to accomplish the function. The function is measured by the performance requirements of the customer and resources are measured in materials, labour, price, time, etc. (NN, 2007) In comparison to e.g. productivity, a standard exists for value (Murgau, 2009).

In this thesis, performance is discussed on more general terms without specifying it to a certain set of measures. In performance, cost is a vital part, but almost any non-cost objective (e.g. quality, speed, flexibility) can be included (Tangen, 2007). In some cases performance are discussed in this thesis in the sense of efficiency and to some extent quality and effectiveness, whereas the other performance dimensions are merely touched upon. Effectiveness is important in a process planning perspective since if an organisation or a process does not produce a service or product that answers to expectations, it has very little value to provide it to the market. As delimitation, this thesis in general considers the effectiveness to be met by the studied organisations and focuses on the efficient use of input resources.

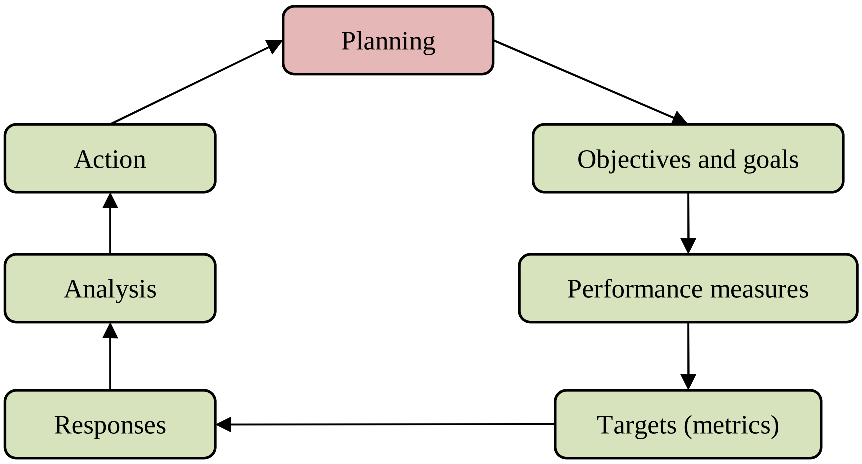


Figure 19. Figure illustrating the integral use of performance measurements of the company organisation. (Bond, 1999)

4 Results and discussion

The chapter starts by presenting the appended papers categorised according to three different criteria and continues by providing a brief summary of the papers. Subsequent chapters present the combined results and a discussion hereof according to the research question of the thesis.

4.1 Paper overview

Table 3 gives an overview of the appended papers according to research objective, method and methodological approach.

Table 3. Categorisation of appended papers

	Paper I - Production preparation methodology in Swedish metal working industry - a State of the Art investigation	**Paper II** - CNC machining process planning productivity – a qualitative survey	**Paper III** - A survey of metal working companies' readiness for performance measurements of process planning work	**Paper IV** - Green machining- Improving the bottom line	**Paper V** - Impact of energy efficiency on CNC machining
Thesis/research question					
Process planning aids		√			
Control/management of process planning			√		
Process planning method	√	√			
Process planning performance	√				
Process planning demands				√	√
Research method					
Empirical survey quantitative	√		√		
Empirical survey qualitative		√			
Conceptual				√	√
Experimental					√
Methodological purpose					
Exploratory	√		√		
Descriptive	√	√	√	√	
Presumptive	√				√
Confirmatory					

4.2 Summary of appended papers

The following section summarises the appended papers in the thesis regarding aim, results and main conclusions. The specific results of individual papers will not be included if not of particular importance for the synthesis. The contribution from the author of this thesis is also briefly stated.

4.2.1 Paper I - Production preparation methodology in Swedish metal working industry - a State of the Art investigation

The paper is based on a questionnaire survey of the Swedish metal working industry. It pointed out a number of interesting questions that need additional research. The main result of the study was that the participating companies only have vague knowledge about their process planning function. Process planning efficiency is subjectively estimated; hence no metrics exist for measuring process planning efficiency. It also pointed out a big potential for efficiency improvements if better information management were to be employed. One of the main hypotheses - whether more systematic process planning leads to more efficient process planning, could not be verified. This is possibly because of the unclear quantification of process planning performance.

Author contribution: The author of this thesis wrote most of the paper. The basic research aim was developed by the co-authors. The survey and data analysis was conducted by the author of this thesis.

4.2.2 Paper II - CNC machining process planning productivity – a qualitative survey

Due to a number of questions that were not possible to answer by paper I due to the employed research method, a qualitative research method was used to create a deeper understanding of the metal working companies' process planning function. The paper is based on interviews with a number of process planners from six different companies, with the commonality of using CNC machining as the principal manufacturing technology. The main result from the paper is an understanding of the investigated companies' process planning automation level. A five dimensional scale was used to map the companies' level of automation. It generated an understanding for process planning development needs and incurring problems. Overall, the use of computer-aids in process planning was low in the investigated companies and consequently a low automation level of process planning work.

Author contribution: The basic research aim was developed jointly by all authors. Interviews and analysis were carried out by the author of this thesis and the bulk of the paper was written by the author of this thesis.

4.2.3 Paper III - A survey of metal working companies' readiness for performance measurements of process planning work

A lack in objective measurements of process planning efficiency, as stated in paper I was the starting point for investigating the readiness for a number of companies to employ a measurement system for process planning. A fundamental part of improvement management is to possess the appropriate and reliable information about the performance of the processes that are to be improved. The paper presents a questionnaire survey to find the presently used performance measures and the infrastructure and readiness of the companies for extending their current measurement system to include process planning performance measures. The paper is of exploratory art and establishes five dimensions of a performance measurement system. Aggregated data from the survey showed that the companies have many short comings regarding performance measurements in general, but also for process planning in particular.

Author contribution: The basic research aim, the survey and analysis were carried out by the author of this thesis. The author of this thesis also wrote the bulk of the paper.

4.2.4 Paper IV - Green machining- Improving the bottom line

Demands on process planning are multidimensional, some stem from customers, some from company policies etc. With the ever increasing importance of environmental awareness and policies, it is important for the process planner to use the available methods to decrease the environmental impact from machining operations. Since the overall objective of the company is to reduce manufacturing cost and remain competitive on the market, it is of greatest interest of the company that reduction of environmental impact comes to low costs. The paper presented available techniques to reduce the environmental impact and especially energy consumption from metal cutting operations, such as the use of dry and semi dry cutting. It also highlights the importance for process planners to have knowledge about specific cutting energy as method to reduce the total energy consumption of machining. The specific cutting energy is a function of machining parameters and machine set-up.

Author contribution: The basic research aim was developed the two co-authors. The writing of the major part of the paper, data acquisition and calculations were carried out by the author of this thesis.

4.2.5 Paper V - Impact of energy efficiency on CNC machining

Similar to paper IV, paper V investigates the potential to reduce the environmental impact from machining operations. However, the focus is only energy consumption, which is the principal environmental impact from machining. The paper has a less technical approach than paper IV and the aim is the investigation of the relation between cost and energy efficiency. An extended machining cost model was developed and the relation was investigated using a turning experiment where machining parameters were modified. The results showed that no inherent contradiction exist between cost and energy efficient machining. This means that to a great extent cost savings can be achieved concurrent with environmental gains.

Author contribution: The research aim was developed by the author of this thesis. Development of the model and experiments were made by the author of this thesis as well as writing the bulk of the paper. Analysis of results was done by the first and second author.

4.3 Investigation of process planning methodology in Swedish metal working industry

Efficiency of process planning work is as described throughout this thesis focused to the used method and the means of implementing better methods to meet a changing environment and increased demands performance. Three of the appended papers (I, II and III) in this thesis concern studies of the Swedish metal working industry. Two research methods were used; questionnaires and interviews, which had influence on the sample size of included companies and the type of questions that can be posed and answered. The principal focus of these studies is the efficiency aspect of process planning and finding the state of process planning work.

Ref. (Halevi and Weill, 1995) described the process planner work activities work activities to be distributed as 15% technical decision making, 40% data, table reading/retrieving and calculations and 45% for text and documentation. This observation was published in 1995 – 14 years ago. During this time, computer-aids have developed considerably. Computational power has increased many times, the integration between CAD, CAE and CAM has increased. The same is valid for the possibilities for model based information management through PLM and other systems. In this perspective, the industry could have made considerable improvement in process planning work, where more time and resources could be dedicated to decision making. However, this could not be observed in the studies performed within the scope of this thesis, although the research did not focus on investigating this specifically. The situation appears to be rather similar to the one observed in 1995. In paper I, information management was pointed out as a major inefficiency of process planning and as much as 27% of the process planning time in the industry is dedicated to data recreation. This is because already created/used information is not systematically reused. This shows that in general there is a need for methodologies and systems that targets this issue. Since the usage of computer-aids in process planning in many companies is rather underdeveloped, there is a need to implement systems where data can be reused, so that tedious manual work can be automated. By using CAM systems rather than manual NC programming, the gain is two folded; first part geometry information (design data) can seamlessly be integrated (if CAD/CAM systems are integrated) and second, less work is dedicated to tool paths calculations. These measures potentially have positive impact on the quality of machining processes and process planning lead time. PLM systems target the working methodological and information management aspect of process planning, but the overall efficiency of these systems (especially on a short term basis) can possibly be questioned, since they often require substantial resources in administration and investments, which in particular for SMEs are difficult costs loads to carry. There is consequently a need for cost efficient systems.

Paper II showed that for some companies, especially sub-contractors with a high share of non-regular customers, interface issues confines one of the problems for automating the process planning function (see chapter 3.5). The customers deliver product data and requirements in shifting format and standards. Paper II also showed that there in general there is little cconcurrency between process planning activities. This is mainly because the relatively small size of the companies, where some of the studied companies only have one process planner. In other companies, most process planning work is still carried out in a sequential manner, thus limiting the possibilities for lead time reductions.

Surveys through questionnaires and interviews as presented in this thesis, have not provided complete information about process planning performance and working methods and appropriate improvement measures to take in order to develop the process planning function. This should not entirely be regarded as a research methodology problem, since it also indicates problems and limited knowledge within the surveyed companies for process planning. This issue is also discussed in appended papers I-III. It is also relevant to ask whether further interviews with metal working companies will generate more generic results so that conclusions about process planning in the industry at large can be drawn. To conduct interviews with a larger sample than conducted would be very time consuming and the results would possibly be difficult to generalise and the results would probably be of limited value. To study the process planning in an even more limited sample and performing more in depth studies and longitudinal studies, during a process planning improvement program would certainly provide more valuable knowledge. Whether the stated problems in this thesis are typical for the Swedish industry in particular or whether it is more of an international problem as well, is worth mentioning. The presented results from interviews in paper II was carried out in three Swedish and three Australian companies and although the sample is too small to make any general conclusions, it did not give any hints of any significant difference in process planning focus between these two countries. It is likely to assume that the problems described and highlighted in this thesis are global and not limited to certain Swedish companies.

4.3.1 The drives for process planning improvements

The way that companies work with process planning aids and development could not be correlated to any of the environment variables identified (see paper I). One possibility is that the efficiency and the use of process aids depend on other factors than the studied, where one possible explanation is the human factor. The involved people in the process planning organisation or other part of the company management and leadership can be the factor that drives the focus on process planning aids and efficiency improvements.

Although the investigated companies claim to have good understanding for the process planning function's influence on company objectives, Paper I indicated a lack in correlation between perceived process planning efficiency and the proportion between information retrieval as part of the total process planning time. This suggests a need for development of a quantification/measurement system of process planning performance. It also suggests more focus the understanding of the importance of process planning for meeting company objectives. The exact content and scope of such a performance measurement system has yet not been presented in any of the papers. However, paper III presents a survey that focuses on available general performance measures in the Swedish metal working industry, their prerequisites and foci for implementation of performance measures of process planning.

As the three papers regarding process planning efficiency have shown, there is little focus on process planning as a strategic function in the company. Each of the papers I, II and III have presented that process planning often is a neglected function. However, the research presented here has not had the scope of putting the process planning function in relation to other company functions (e.g. accounting, design, engineering, and manufacturing) and therefore it cannot be verified that other functions are treated with the same unawareness. However, paper III presented a survey over companies' work with measurements of process planning and manufacturing and the result supports the notion that measurements as a method to gain process knowledge, is not widely used and the scope of measurements are limited.

Effectiveness has not been the principal objective in this thesis (and in appended papers) – partly because it is even more a matter of organisational priorities and arbitrary in its nature in relation to efficiency. Effectiveness is thereby more difficult to target in surveys (see chapter 3.11). On a company level, process planning can be regarded as a function within the company where the product is a process plan. In this perspective, quality and machining time etc. are parameters of the effectiveness of process planning – how well the process planning function produces process plans that fulfil the company requirements and ultimately customer demands.

Flexibility and process planning – Better flexibility can be reached with a more efficient process planning function, where resources are better utilised, information retrieval is efficient so that process planning lead time is shortened, so that process planning can meet different types of input flexibility.

4.4 Environmental aspects of process planning

The main contribution from this thesis regarding environmentally benign manufacturing refers to energy savings in CNC machining. By increased knowledge of process planners, the machining processes can be optimised for cost and energy efficiency. Minimised process waste and better utilisation rate of the machines, so that standby times are lowered, will work in favour to advance towards more environmentally benign and lean production. In this thesis, the focus is on process optimisations to meet increased demands on energy savings and cost reductions. The two papers (IV and V) only consider the direct machining aspects of energy savings and excluding the indirect ones (as utilisation rate, standby etc.). One important aspect of using higher removal rates and higher throughput times as means to increase cost and energy efficiency also have consequence for the economy of scale, in that the machine availability increases due to shorter cycle times. Paper V provides a dynamic model for calculating the energy consumption in relation to different machining cost components, which other environmental cost models do not. For example Life cycle costing (LCC) does not regard the energy cost as variable, dependent on different machining strategies, thus providing little understanding for how various costs are related and can be influenced (Enparantza, Revilla et al., 2006; Dervisopoulos, 2008). Traditional machining cost calculation methods (which paper V's cost model is based on) on the other hand do not give information about energy consumption under different machining parameters in relation to other costs. The results from paper IV and V show that, not entirely new methods need to be employed regarding energy efficiency, since the environmental benefits to a great extent follow the economically beneficial curve. There is a tendency to internalise external environmental costs from a governmental side, which means that future environmental demands to some extent will be introduced via the prices of various products and services. For example increasing fuel taxes and carbon dioxide emission trade caps will influence the price of raw material and energy use etc., hence the importance to minimise the cost of these parameters are enhanced.

As described above, papers (IV and V) provided directions and guidelines for the process planner for machining parameters selection in order to achieve energy and cost efficient machining. However, the investigation is not complete. There are a few areas that would need further research in order for establishing a complete understanding for green machining in the sense of the relation between cost and environmental aspects. The experiments were limited to turning operations, one material, excluding use of cutting fluids.

4.5 Process improvements – what are appropriate measures to take?

The highest and in an automation perspective ideal state of process planning can be considered the fully automatic stage, where a product model is the input and a complete and optimal process plan is generated without requiring any human intervention. As described in paper I and II, the present industrial situation is far away from this scenario. For rather simple products process plans can be automatically generated through various program algorithms. However, with increasing product complexity and internal and external requirements, these possibilities vanish. Natural questions are; if this state is ever possible to reach?; and if yes, what would the time horizon be? These questions are important since two principal improvement routes appear. The one, as already mentioned – complete automation and the second – development of human-centred semi-automated process planning aids. The latter is more in the line of the philosophy of continuous improvements, while the first is more of breakthrough character. What are the appropriate measures to take to develop process planning into the future, with increased demands on cost efficiency, flexibility, product quality and environmental friendliness? For the general subcontractor company, where demand and product flexibility is high, the fully automated stage, appear distant. For companies with rather defined products, input and customers, but with high complexity the fully automated stage also appear distant, since their competitiveness often are defined from their skill for innovative machining solutions and ensuring high quality etc. A fully automated CAPP system, where its nature of interpolations rather than extrapolations is allowed, would not benefit innovation in machining techniques. The industry branch where full automation appears most likely is where companies work closely with regular customers (to ensure homogenous input), product complexity is lower, machining lead times plays a secondary part and demands for innovation and new technology is rather limited.

There is an inherent problem with process planning development when the company's knowledge about the process planning function is a limited as it appeared in the surveys, since improvements and investments cannot systematically be evaluated. In this perspective it is important to have knowledge about resource use for producing a process plan, so that investments in computer-aids and other technological investments have a reasonable pay-back time. If investment and process planning developments cannot be economically justified it will be difficult to defend extra spending. For a manufacturer of high cost products as many manufacturers of aerospace component, where one machining error may incur a cost of one million SEK, only in product cost, it is easier to economically motivate investment in process planning aids. The avoidance of one error can roughly carry the whole investment cost. The above example refer to the quality aspect of process planning improvements, but as discussed extensively throughout this thesis, process planning efficiency and effectiveness are other aspects for making improvements. This can be illustrated in analogy to Figure 4, where *investment cost* can replace *explorative process planning cost* in the figure. The investment costs must be lower than the reduction in machining process planning time and cost. Support and maintenance of computer process aids must be included in the investment costs, since some of the systems require substantial resources to run. Parameters that influence the profitability of process aids investments are: company size, number of process planners, number of produced process plans (novel, recurring and revisions), production batch size, product complexity (nominal process planning time) etc. A company that possess substantial knowledge about the above should make an investment assessment to investigate whether investments can be justified. A company that does not have the required knowledge will not have the same possibilities of assessing the investments and thereby must act more on gut feeling and 'guestimations', which can prove to be a risky project.

Problems with process planning performance can principally come as consequence from three different areas:

- Competence (individual process planner and organisation)
- Working methodologies
- Process planning aids (Computer aids, checklists etc.)

Depending on the type of shortcomings, different measures must be taken to manage process planning improvements. The surveys conducted within the scope of this thesis have been focused to understand companies' working methodologies and available process planning aids. As stated in papers I-III, there are several deficiencies regarding these aspects, e.g. limited use of automated tool path generation, PLM system, measurements and limited management of the process planning function. The competence level of process planner has not been studied or evaluated in this thesis. However, as stated above it is an important area in process planning efficiency and effectiveness. Without becoming fully engrossed in the vast area of knowledge, the competence of process planners can principally be divided into two knowledge categories. The first is the methodological knowledge and the second is the technical knowledge (Figure 20). Depending on the competence level (the ration between the two), the performance of the process planning function will differ and efficiency and effectiveness in influenced. Methodological knowledge refers to the ability to understand the procedure of process planning, how various activities and factors influence performance and the act of planning. This is an important area in respect to the continuous development of the process planning function. Technical knowledge refers to the act of planning a process that is technically optimal, regarding tools, machining parameters, tool paths etc. Process planner experience often refers to this. Indications from the performed surveys give that there are areas for improvements, especially in the selection of tools and machining parameters. The process planner is often dependent on tool vendors and/or use established parameters. Often tool life is the optimisation criteria and machining parameters are adapted accordingly to ensure robust processes. This potentially leads to more conservative machining processes, where machine capacity is not optimised for the product output. A higher level of the technical competence regarding metal cutting, would contribute to better machining processes and output, thus higher effectiveness. The efficiency of process planning would likely increase as well, since the chances for generating an error free and optimal process plan the first time increases; the need for iterations decreases with more skilful process planners. The competence level is typically important in a human-based process planning function. Revisions of process plans are one way to improve established machining processes, so that best available technology (tools and machining parameters) are used. This should be initialised by the own company in a systematic way. As it is often carried out today, revisions are made when customer demands lower costs or when e.g. tool vendors give suggestions for improvements.

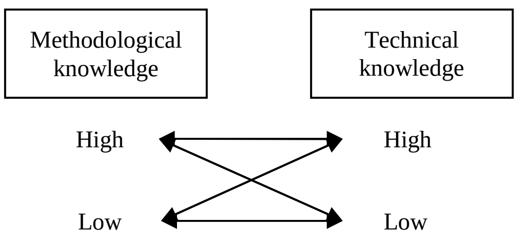


Figure 20. Two types of process planning knowledge

To closer study process planning work through time studies could give important information about the ratio between value and non-value adding activities and which activities that need support and development. Paper I pointed to substantial improvements in information management in the Swedish metal working industry, since much process planning time is dedicated to information recreation, which typically is non-value adding work. A possible solution is the implementation of some PLM system or better working methodologies and routines for information management (storage and retrieval). Another aspect of information management is the management of requirements, how these are presented to the process planner and how this influences the output (process plans and products that correspond to the input requirements). The research presented in this thesis has mainly considered an organisation with dedicated process planners. However, it also exist organisations where the machine operator and the process planner is one and the same. This situation implies some differences regarding the development of aids. The major difference is that the operator is not an expert in process planning in the same way as a dedicated process planner is. The operator does not produce process plans with the same frequency, since process planning is only a part of the work. This is consequently an area where further research should be conducted to enhance the understanding.

A possible implementation strategy of process planning aids could be to start with reoccurring products or simple products and develop strategies on how to prepare those and from here start to reduce process planning lead times. To do so, some sort of measures and metrics should be used to verify that the development is profitable and gives the desired effects. Figure 21 illustrate a possible human-centred process planning environment, where its relation to system aids and control functions are included. A fundamental part of KBE is the systematic reuse of engineering data (chapter 3.10), which must be a part of an improved process planning system as well. Performance measurements (of process planning efficiency and machining and product effectiveness) fed into the process planning control.

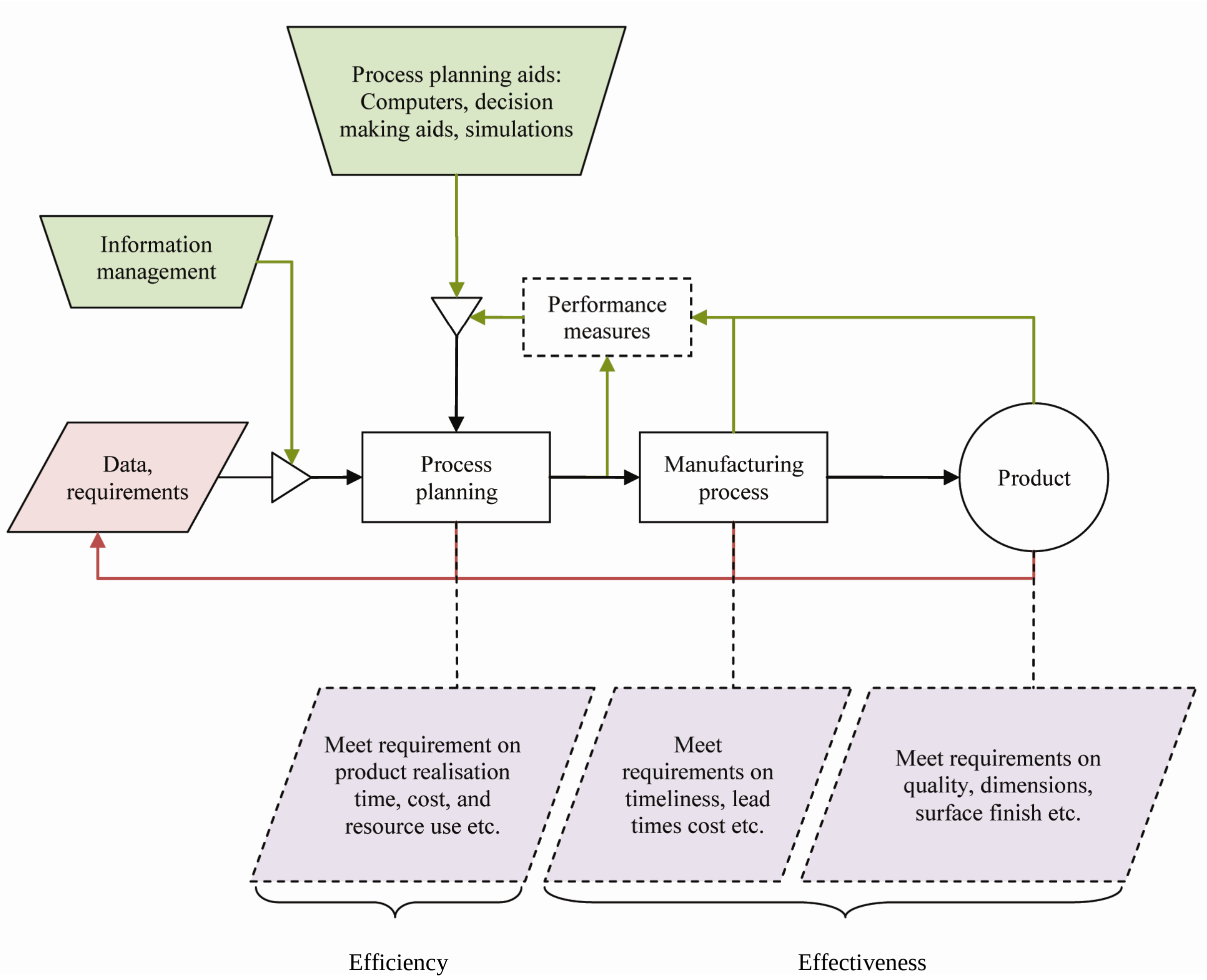


Figure 21. Conceptual understanding of process planning, aids, controls, knowledge feedback and performance measurements as part of a competitive process planning function.

Figure 22 shows a revised version of Figure 12, where appropriate process planning aids, as described in this thesis are included. If the right aids are given, the efficiency of process planning will increase. Better knowledge of data classes will reduce the need for unnecessary simulations and tests, since the process planner knows whether the data was extracted from handbooks, cutting tests or a real manufacturing situation. This is supported by a PLM system that classifies data. The PLM system also manages data and activities, so that correct data are put into the right functions. If non-value adding activities are automated and managed efficiently though described aids, time and resources can be dedicated for decision makings (Figure 22). Since the process planner becomes the centre of gravity, regarding key decisions, the competence of the process planner consequently becomes essential for the effectiveness of process planning. It is then a matter of ensuring appropriate education and working methodologies to process planner to be successful.

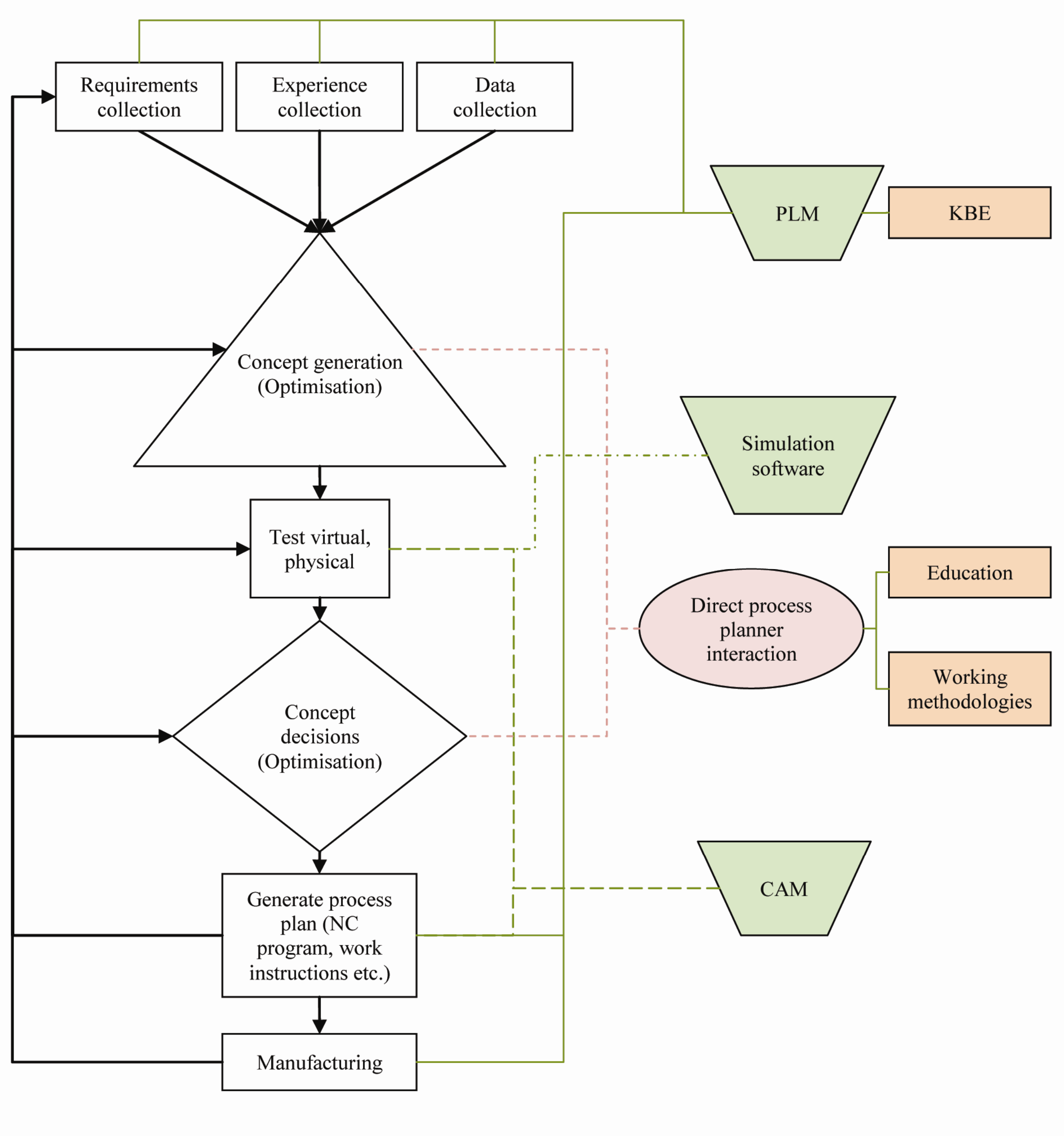


Figure 22. Revised version of Figure 12, where possible process planning aids are included for efficiency improvements.

5 Conclusion

This thesis has presented major characteristics of process planning work in the Swedish metal working industry. This has given a better understanding for appropriate measures to take regarding improvements. The main focus of performance has been on process planning efficiency, but effectiveness has also been considered. The thesis has presented an approach to reach higher process planning efficiency and effectiveness through the design of process planning aids developed around the process planner; human-centred process planning aids. By focusing on reducing the resources spent on non-value adding process planning activities, more time can be spent on decision making activities that adds value in a process planning perspective. The main findings presented in this thesis are:

- A correlation between systematic process planning and perceived process planning efficiency could not be found in the Swedish metal working industry. This opens up for studies of other possible explanations for process planning efficiency.
- Despite a long history of process planning aids (CAM, CAPP and PLM), few of these aids are used in the industry, where manual process planning activities are more common.
- Improvements of process planning performance are difficult in the metal working industry, due to a lack of performance measures. This means that the objective knowledge about the process planning function is limited. Consequently, the impact from improvements on performance cannot be verified.
- Future increasing customer and governmental focus on environmentally benign products and production, where energy efficient machining operations are one important aspect, can also to a great extent correlate the cost reduction focus of machining operations.

5.1 Areas of contribution

- Increased understanding for process planning and automation of process planning activities. Important aspects of future challenges of process planning were highlighted.
- Cost and energy efficiency in machining
- A further developed research question

6 Future work

From the content and results from the thesis, three major disciplines can be identified that needs further research (Figure 23). The presented environmental aspects in this thesis mainly concern electrical energy use, and to some extent the use of cutting fluids. This is an area where further and more comprehensive investigation of various machining parameters, auxiliary functions etc. can increase the understanding for the environmental aspects of machining and thereby their influence on the process planning act. It is important to focus on the development of human-centred process planning aids, which are flexible and scalable, so that present and new demands and requirements, such as environmental demands can be managed with high performance.

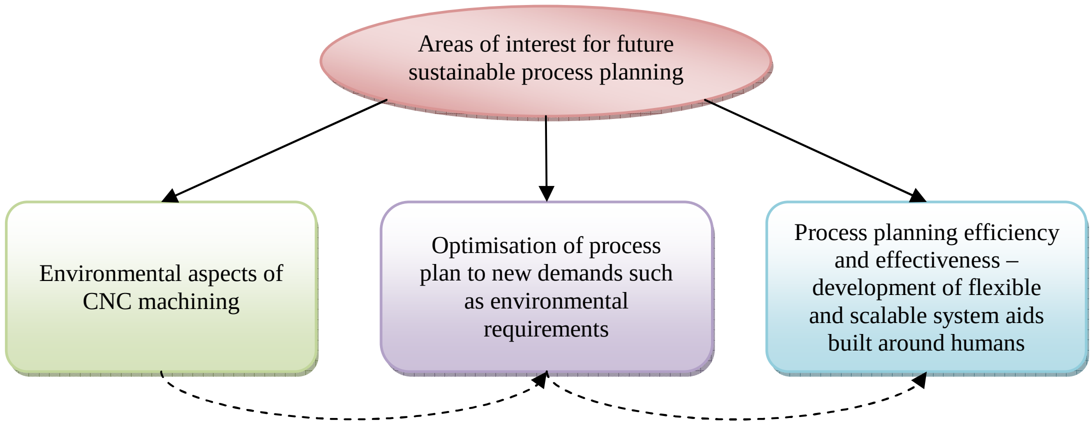


Figure 23. Three possible future research activities within CNC machining and process planning.

6.1 Research questions

The above presented results and discussions generated a set of new research questions that require due answers for creating a more complete understanding for the design of a human-centred process planning system. These questions are:

- How should process planning aids be designed where certain non-value adding activities are automated?
- How should new work procedures be designed?
- How should a measurement system to measure process planning efficiency and effectiveness be designed?

With the introduction of a human-centred process planning system, a few sub-questions follow that are of interest in a company perspective. These are:

- What is the impact of the company organisation?
- Are new competences required?

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