THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Methods for improving performance of process planning for CNC machining
- An approach based on surveys and analytical models

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Abstract

Process planning as an enabler of competiveness is often overlooked, but being one of the principal function in the product realisation flow it holds a key role by combining both product and production requirements into a production concept with respect to the current manufacturing system. As such the capability of process planning to a large extent dictates production cost, lead times, product quality etc. With the introduction of new demands on production, such as environmental impact and process capability, process planning must be able to manage these demands effectively. Accordingly, it is vital to study the effects that up-coming demands have on the act of process planning.

The research methods employed in this work include surveys (questionnaires and interviews), industrial case studies and experiments to provide data for models developed.

The main finding of this research is that there is a lack of quantified process planning performance knowledge in the industry, which leads to verification problems as to whether changes that are made render anticipated effects. Results of surveys also indicated a low level of digitalisation of product data and limited use of computer aids (CAM, feature-based CAM and PLM) in Swedish industry based on 144 companies' response. A concept to improve process planning performance through operation classification based on process capability indices (C_p/C_{pk}) was suggested. The role of process planning in designing cost efficient and energy efficient machining operations has been maintained throughout the thesis by showing how tool selection and machining parameters selection influence the possibilities to achieve these objectives. This work has also showed that no inherent contradictions appear to exist between achieving cost efficient and energy efficient machining operations.

This thesis has contributed to an enhanced understanding of how process planning improvements can be achieved through a holistic perspective of the process planning function, where both technical and methodological aids are included. It is however essential to understand the current situation of the process planning organisation, its internal/external relations, level of digitalisation, competency level etc. before major changes of the process planning function are undertaken in order to be successful.

Keywords: Process planning, CNC machining, metal cutting, performance, process capability, environment, energy

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The research would not have been possible without the help of all the people in the companies that make up a substantial part of the presented research. All the colleagues at PTC should not be forgotten, which have contributed to the excellent work environment. And last of course, my dear Elvira. Thank you.

Five years is a long time… During my first five years I learned to talk, walk and play. The last five years I have also learned a lot… About myself, others, my area of research and lecturing. The last five years, it could be argued, were probably not as groundbreaking for my personal development as the first five. However, I enjoyed them immensely and can still remember most of them, which I cannot say I do from the first five.

The first five years saw me growing into an independent human being and the last five into an independent researcher.

Staffan Anderberg

Trollhättan, March 2012

List of acronyms

ABC	Action Based Costing
APT	Automatic Programmed Tooling
BLISK	BLaded dISK
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer-Aided Process Planning
CE	Concurrent Engineering
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CO_2	Carbon Dioxide
CoPPR	Cost of Poor Production Rate
CoPQ	Cost of Poor Quality
DMAIC	Define Measure Analyse Improve Control
ERP	Enterprise Resource Planning
EU ETS	European Union (greenhouse gas) Emissions Trading System
FMEA	Failure Mode and Effects Analysis
FMS	Flexible Manufacturing Systems
GD&T	Geometric dimensioning and tolerancing
KBE	Knowledge Based Engineering
LCC	Life Cycle Costing
LSL	Lower Specification Limit
MQL	Minimal Quantity Lubrication
MRR	Material Removal Rate
NC	Numerical Control
ODM	Original Design Manufacturer
OEM	Original Equipment Manufacturer
PCA	Principal Component Analysis
PCD	Physical Chemical Deposition
PCI	Process Capability Index
PCR	Process Capability Ratio
PDM	Product Data Management
PLM	Product Lifecycle Management
PVD	Physical Vapour Deposition
QFD	Quality Function Deployment
SBCE	Set-Based Concurrent Engineering
SME	Small and Medium size Enterprises
SPC	Statistical Process Control
USL	Upper Specification Limit
WIP	Work In Process

List of notations

a_p	Depth of cut
B_m	Burden rate of machine tool
C_{CO2}	Carbon dioxide emissions cost per piece
C_{ED}	Direct electrical energy cost per piece
C_{EID}	Indirect electrical energy cost per piece
C_i	Idle cost per piece
C_{it}	Tool change cost
C_m	Direct cost for machine tool and labour per produced piece
C_M	Cost for a particular machining operation
C_p	Process Capability Index
C_{pk}	Process Capability Index (including process centring)
C_{PP}	Process planning cost for a certain machining operation
C_s	Set-up cost per piece
C_t	Direct tool cost per piece
CES^{TM}	Carbon Emission Signature
D	Diameter (of a workpiece)
ΔT	Machining time saving due to explorative process planning time
E_D	Direct electrical energy consumption
E_{ID}	Indirect electrical energy consumption
E_T	Embodied energy of cutting tool
E_{TC}	Embodied energy of cutting tool coating
E_{TM}	Embodied energy of cutting tool material
f	Feed rate
i	number of edges per insert
K_{CO2}	Carbon dioxide emission cap and trade cost
K_E	Electrical energy cost
K_h	Tool holder cost
K_i	Tool insert cost
K_m	Machine and labour cost rate
L_m	Fully burdened labour cost rate
L_{PP}	Hourly process planning cost rate
m	Cutting insert mass
M_m	Machine cost rate
n	Revolutions per minute
N	Production volume/batch size
N_h	Tool holder life
N_o	Number of operators per machine
r	Pearson product moment correlation coefficient
t	Undeformed chip thickness
T	Insert tool life
t_c	Tool change time
$T_{explorative}$	Explorative planning time for a certain machining operation
t_i	Idle time
t_m	Machining time
T_M	Machining time for a certain operation
$T_{routine}$	Routine planning time for a certain machining operation
t_s	Set-up time
V	Volume of removed material
η	Efficiency
μ	Mean of process
σ	Standard deviation

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Part I

Research formulation and research problem

1 Introduction

This chapter introduces the area of research and its relation to adjacent areas and importance for the development of the manufacturing industry. The chapter also contains the aim, the research questions and the research approach and methodology for this thesis.

1.1 Background

The Swedish manufacturing industry faces ever increasing competition from regions with low labour costs and from companies that employ leaner manufacturing organisations that cut costs through elimination of waste and improved quality. To maintain their competitiveness, companies must also be able to meet new regulations regarding e.g. environmental protection and to adapt to increasing prices of raw materials and energy.

To meet changing market demands, it is essential for an industrial organisation to be able to optimise its operations, product development, process planning and production for the current situations. New and improved production methods and technology must be incorporated rapidly to avoid becoming obsolete in comparison to competitors. From a process planning perspective, this e.g. may imply the utilisation of new machine tools and cutting tools introduced to the market, while at the same time new materials are introduced to enhance product performance but which are sometimes more difficult to machine. More advanced product geometries and assemblies add further to production difficulties. Altogether, these changes impose new and sometimes challenging demands on the production process. Methodologies must exist or be developed within the process planning organisation to effectively adapt to the swiftly changing environment. An efficient process planning function must be able to manage large quantities of information regarding e.g. the machine tool, cutting tool selection, machining parameters, machining strategy and workpiece clamping. The parameters defined and the decisions made during process planning to a great extent dictate the productivity and cost efficiency of the machining process, as well as its environmental impact.

The various activities involved in creating a process plan that contains the NC program and instructions necessary for additional work activities to produce a part through CNC machining are called process planning. Process planning in relation to other activities within the company can be illustrated as an intermediary function between design and production (Figure 1.1). Process planning can then be regarded as all the activities necessary for giving instructions on how to bring a virtual product into the physical world.

CNC was one of the most important innovations in the manufacturing industry in the 20th century, since it automated many of the machinists' tasks. It enhanced the design freedom and process repeatability and it reduced lead times in production. CNC technology was and still is an enabler for mass production as well as small series production of almost any geometrical shape. Manufacturing and computer numerical control (CNC) machining plays an important role in the Swedish economy. In 2010 Sweden was the 8th largest global buyer per capita of machine tools, with a total spending of some 1.6 billion SEK (Gardner publications inc., 2011). One of the major drawbacks of CNC machining is giving instructions to the machine, which requires skilful programmers who must not only understand computer-aided manufacturing (CAM) or NC programming, but also have extensive knowledge about machining (Yeung, 2003), i.e. theoretical and practical knowledge about metal cutting principles. Machining knowledge includes knowledge about tool selection, machining parameters, vibration and cooling, etc. Whereas tool paths (in the form of NC code) can be generated efficiently by most CAM systems, technical planning is often tedious and requires much data, information and decisions to generate efficient machining processes.

Implementation of computer aids such as product lifecycle management (PLM) systems provides a foundation for information and data management as well as coordination of work activities within processes. However PLM implementation in industry is still not complete (Denkena et al., 2007).

Halevi (2003) states that "process planning is often seen as an art and not a science". A consequence of this situation is that there is little uniformity of working methodologies, so that two process planners will most likely not deliver the same process plan for a given part and set of requirements, although both plans may fulfil the specified requirements. Modern technology has radically changed the human skills required. Due to the more intellectual activities involved in many jobs, the need for strength and motor performance has become less important. Instead, intellectual skills such as judgement and decision making have become crucial human elements (Slovic, 1982). This is highly relevant for the manufacturing industry.

Today there is a shift from more labour intensive work (blue-collar) to work based more on knowledge (white-collar). Human productivity is therefore becoming more and more a matter of efficient information processing and decision making (Howell, 1982). In a production organisation, this means that the use of CNC machines reduces the need for personnel in the actual operation of machines; instead, machine monitoring is becoming the main work task. Machinists are to some extent being replaced by process planners that do not directly work with the machine and its operation, and hence there is a difference in skills. However, in many cases operators are promoted to process planners and it is also not uncommon in small and medium enterprises (SMEs) that the process planner and machine operator is one and the same.

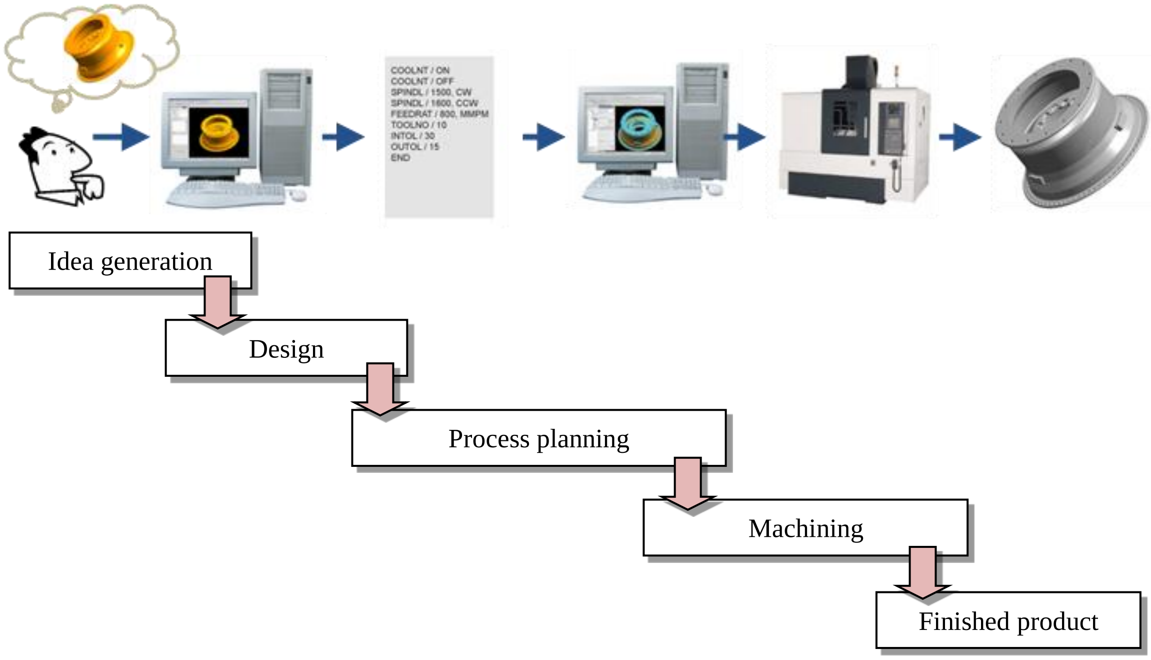

Figure 1.1 The principal product realisation flow chart for machined components using concurrent engineering. The arrows illustrate the data and information as well as constraints and requirements generated in each step.

To date, the main research effort in lean production has been in the physical production itself, and less attention has been paid to advancing lean thinking into the domain of engineering and administrative work. Murgau (2009) and Murgau et al. (2005) studied the importance of engineering work for understanding company performance (in the form of value creation). It was found that a significant part of the work activities in a production engineering department consisted of making selections, retrieving, understanding and structuring information before processing it (Murgau, 2009). Although the efficiency of knowledge work is important, it is essential to include the output of the processes as well. Considering only process planning and neglecting production output can prove to be counterproductive, since it is output that the customers base their buy or not buy decisions on.

Altogether it is a complex situation, where different company levels and requirements must be regarded in order to optimise output. Figure 1.2 provides an overview of process planning aids as means to improve performance quantified as six performance objectives as defined by Slack et al. (2004), with the addition of the environment (motivated in the following section). Many of these aids can be applied to achieve overall high performance, but the extent depends on factors and prerequisites of the individual company.

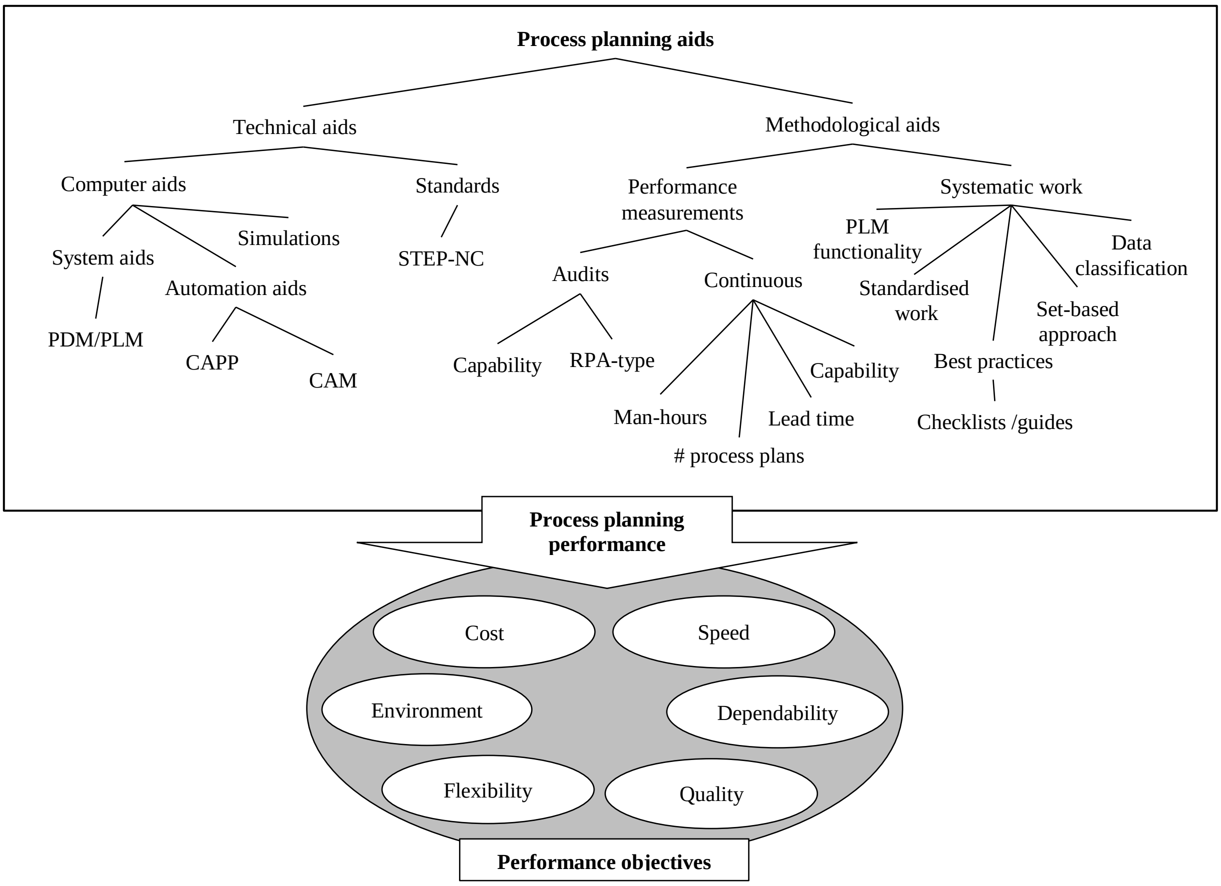

Figure 1.2 Overview of process planning performance improvement methods in relation to performance objectives.

A company's success is frequently measured in economic terms such as profitability, return on investments, cash flow etc. However, other metrics can also be included. Recently environmental and social aspects have been receiving more attention, which together with economy is called sustainability or the "triple bottom line". The work presented in this thesis focuses on the economic and environmental aspects of sustainability, where energy use is employed as indicator of environmental aspects of CNC machining.

Dornfeld (2011) discusses the incentives for, and the importance of making improvements in the manufacturing process, albeit the total environmental impact in comparison to the product lifecycle may be relatively small for certain product types. This can be exemplified by automobiles, where the use phase can account for 80% of the total environmental impact (including emissions of carbon dioxide, nitrogen oxides, sulphur dioxide, dust particles and non-methane volatile organic compounds etc.) and manufacturing only 20% (Dornfeld, 2011). Nevertheless, for the individual company the environmental impact can be considerable and the potential savings in e.g. energy consumption can be substantial and financially defendable. The trends in the automotive and aerospace industries are that significant reductions have been made in the use phase and so, unless energy savings are made in the manufacturing phase, the latter will be responsible for a larger proportion of the total environmental impact in the product lifecycle. The Swedish Energy Agency (Energimyndigheten, 2011) reports that the industrial sector accounts for 40% of the total energy use in Sweden, with electricity and biofuels as the main energy sources. With rising electricity prices (Figure 1.3), there are, besides the strictly environmental benefits also economic gains to be achieved through energy rationalisation.

The main opportunity to determine environmental performance can be found in the product design phase, since it is the product design that controls both the environmental performance during use and during production, and hence the total product lifecycle cost. Process planning, which in itself cannot directly influence the environmental impact during use, can however significantly influence the environmental impact during production, as will be further described in this thesis.

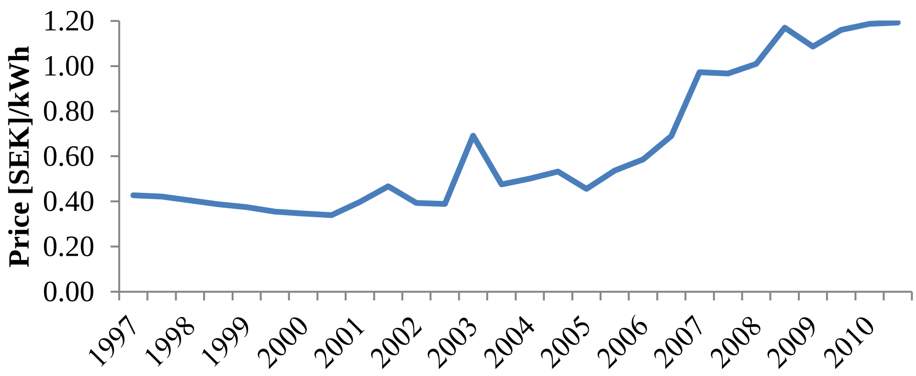

Figure 1.3 Industrial electricity price trends in Sweden (tax incl.). A new calculation method was introduced in 2007, causing inconsistency in prices, hence the price jump. Ref. (Swedish Statistics, 2011)

1.2 Problem identification and research question

The starting point of the research stems from an industrial need where the research director of Volvo Aero Corporation had discovered that process planning for CNC machining of a typical aerospace component required tens of man-years of work. Even more surprising was that when production of the same component type was transferred to a different machine tool, the process planning need was still approximately the same and equally as immense. Despite a plethora of computer aids and simulation tools available for the process planners, the problems still lingered. What was the reason for this? This spurred the initiation of a research project targeting issues related to process planning efficiency and methods for improving process planning performance.

The general objective when this research commenced was to investigate working methods and aids for process planning in a complex manufacturing environment. The industrial need identified was transformed into the set of research questions described below, but where the overarching research question was the following:

How can process planning for CNC machining with a focus on production performance be improved, and in which operations with and without prior knowledge are managed effectively?

The production performance parameters investigated are process capability, total cost of machining and energy efficiency. This more general research question was complemented with a set of subsidiary research questions, each targeting a more limited area (Table 1.1). The production methods considered include metal cutting processes such as milling, turning and drilling, although some of the content of this thesis may also be applicable to other manufacturing processes.

Table 1.1 Research questions and rationale.

Research questions	Rationale
1. What are the principal process planning deficiencies in the industry?	This was the starting point of the research aimed at describing the general situation in the industry.
2. What are the available process planning aids and to what extent are these used in the industry?	Initially the work was based on a broader approach to the industry, but the scope was subsequently narrowed to a more in-depth understanding of individual companies' process planning work.
3. What are the possibilities for concurrently meeting stricter demands on low total machining cost and energy efficiency?	Energy use is the main environmental impact of CNC machining, and process planning decisions significantly influence the outcome in terms of lead times, costs and energy use. A more comprehensive description of these factors is valuable.
4. How can an improved process planning methodology decrease operator dependency in CNC machining through the design of more capable processes?	For increasing the level of automation and improving machining performance, process capability was selected to be further studied from a process planning perspective.

Research work progression

The first two questions were the starting point of this research, where the aim was to better frame the field of process planning and to describe process planning from an industrial perspective, with a focus on planning efficiency, i.e. efficient use of human resources.

The third question focuses on how process planning decisions can influence and create opportunities for more environmentally benign machining. Energy efficiency in relation to total cost of machining was selected as the main parameter for this part of the research. This relation is a key to understanding whether new process planning methods must be developed specifically to achieve energy efficient machining processes, or whether conventional approaches to process planning are sufficient.

The fourth question is important for creating manufacturing processes that reduce the cost of poor quality by increasing the reliability and consistency of production. High process capability is also a facilitator when advancing towards higher automation levels. In the two latter questions the focus shifted from efficiency to the effectiveness of process planning.

The study field of process planning is vast and a multi-disciplinary research approach must be employed in order to retain a holistic perspective. Most of the published research however is limited in its scope and the bulk of work is limited to the development of CAPP/CAM systems, algorithms, data exchange models and standards, whereas much less work has targeted aspects of system integration and managerial aspects of process planning work. In order to achieve high overall process planning performance, this should not be an entirely empty field.

Due to the multi-disciplinary nature of the research field, several research methods have been employed to capture the different aspects. This is further discussed in the following section.

1.3 Research approach and research method

Due to the complex nature of process planning which ranges from strictly technical aspects to the human intellect and organisational issues, the research methodology becomes somewhat less straightforward as well. Research on process planning performance in industrial organisations cannot exclusively focus on the technical aspects of process planning, but must also include the organisations and their respective prerequisites. This requires that different research methods are employed in order to be able to capture each aspect of process planning. This thesis is essentially a product of research work in the form of surveys, theoretical analyses and experimental work. A short review of the research methodology, its features and to which parts of research it applies is given below.

Qualitative and quantitative research methods are frequently compared, where the latter is often seen as being superior in generating empirically reliable and valid results. In many cases both qualitative and quantitative methods are complementary and together give more reliable results (Bachiochi and Weiner, 2004). Although qualitative studies stem from the social sciences, they have been adapted to many other fields as well. Qualitative research is distinguished from quantitative research mainly in the act of observation and analysis, where observations are often made through the use of structured and semi-structured interviewing techniques (Locke and Golden-Biddle, 2004). The advantage of conducting interviews is the flexibility in e.g. question sequence, level of detail, explanation and the possibility to follow-up particular answers, which enables more complex surveys to be carried out (Forza, 2002).

In quantitative research through surveys, the response rate is an important measure to judge the survey success rate. Low response rates increase the risk of bias in results, where extracted data may only represent prosperous companies (Frohlich, 2002). The response rate is related to the validity of the research, where validity deserves a bit more attention, since there are many more aspects of validity than the response rate and sample size alone.

Validity can be defined in terms of e.g. internal, external and construct validity. Method triangulation is one viable option for increasing internal validity, where different research methods such as questionnaires and interviews are used and where findings are compared (Croom, 2009). Croom (2009) also states that external validity refers to the generalisability of results and conclusions drawn. Croom (2009) further mentions the importance of population and temporal aspects. External validity is also often referred to as reliability. The temporal aspects of survey research relate to the risk that findings are only valid for that certain period of time when the research was conducted. Research in industrial organisations seeks to describe the characteristics of the organisation as a whole on a department, plant or company level. However, surveys must be answered by people working in the organisation, since the organisation in itself cannot provide answers. Due to the functional specialisation and hierarchical structure of companies, it is important to identify the right persons who can provide the most accurate information about the specific subject (Forza, 2002). This last aspect can be placed under the population aspect of validity. To this is added the factor that given answers may be influenced by the individual respondent's perception. Croom (2009) further brings up construct validity, which refers to whether or not research activities actually manage to measure what was intended. In questionnaire surveys there is always a risk that questions and terminology are misunderstood or misinterpreted. This risk is smaller with interviews since there is bi-directional communication.

Another key aspect of validity is the intersubjectivity of the research, which is of particular relevance in survey research. Intersubjectivity refers to the results and their independence from the researcher - that similar results will be produced regardless of who carries out the research (Gilje and Grimen, 2007). As a consequence of the aforementioned; care must be taken when conclusion are drawn from studies of organisations.

The research presented in this thesis includes both qualitative and quantitative research, where questionnaires were utilised to enable a larger sample of companies. Altogether three questionnaire surveys were produced, where the number of respondents ranged from 12 to 144. Qualitative methods, such as interviews and observational studies, were used to in depth study the planning process and operators in a more limited number of companies. Observational studies and machining experiments provided data for models developed for analysing process capability and the relation between cost and energy efficiency in CNC machining. Machining experiments for the studies on energy use in CNC machining were conducted in the manufacturing laboratory at the School of Mechanical and Manufacturing Engineering at the University of New South Wales, Sydney.

More information and data regarding research methods are given in connection with each presented part. In section 6.1.5 the validity and intersubjectivity of results is discussed from a research method perspective. In conclusion the following research methods have been applied to the following works presented in this thesis:

- The first area of research targets the state of the industry in terms of process planning, where questionnaires and interviews are the research methods used.
- The second area investigates means to improve process planning performance, which primarily use case-studies and models as research methods.
- The third area focuses on process planning in relation to new and upcoming demands on production (mainly energy efficiency and capability), where the research method is testing analytical models through case studies and laboratory experiments.

1.4 Outline of the thesis

This thesis is a monograph and the aim has been to provide a thorough overview of process planning as whole and to present the great complexity therein. The thesis is divided into four parts, which are described below and in Figure 1.4.

- The first part establishes the area of research by providing a background to the field of study and outlining the research approach and research questions.
- The second part aims at contextualising process planning and describing its position in the manufacturing organisation and ways to improve process planning performance. The second part may appear obvious to persons experienced in process planning. However, for the inexperienced, this part should provide a solid background so that the complexity of process planning for CNC machining can be comprehended.
- The third part presents the research and empirical results. This part has been divided into different sub-parts, where individual results of surveys and experiments constitute the first section. Thereafter follows discussion/synthesis of the research and the third part finishes with the conclusions drawn.
- The fourth and last part consists of appendices to provide complimentary data developed during the research as well as additional equations.

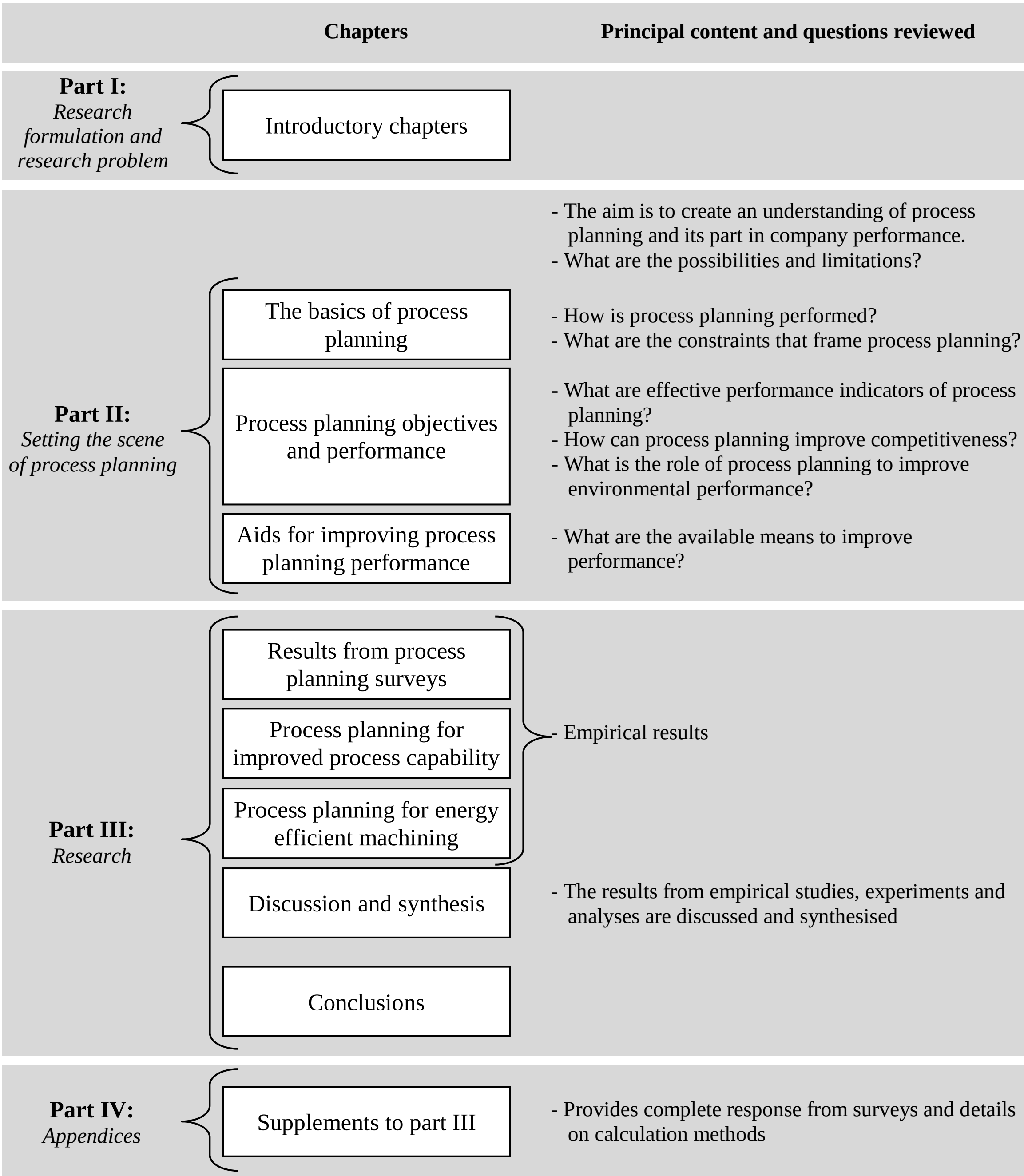

Figure 1.4 Disposition and scope of the thesis.

1.5 Publications

Despite being a monograph, the research presented in this thesis is based on a number of publications. These publications and which parts of the thesis that corresponds to which publications are briefly outlined below. These papers provide further information than what is provided in this thesis on some of the subject areas.

Paper I: Anderberg, S., Beno, T. and Pejryd, L., 2008, *Production preparation methodology in Swedish metal working industry - a state of the art investigation*, Swedish Production Symposium 2008, Stockholm, Sweden: section 5.1.1

Paper II: Anderberg, S., Beno, T. and Pejryd, L., 2009, *CNC machining process planning productivity – a qualitative survey*, Swedish Production Symposium 2009, Göteborg, Sweden: section 5.1.2

Paper III: Anderberg, S., Beno, T. and 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, China: section 5.1.3

Paper IV: Beno, T., Anderberg, S. and Pejryd, L., 2009, *Green machining – improving the bottom line*, 16th CIRP International Conference on Life cycle Engineering, Cairo; Egypt: section 5.3

Paper V: Anderberg, S. and Kara, S., 2009, *Energy and cost efficiency in CNC machining*, 7th Global Conference on Sustainable Manufacturing, Madras, India: section 5.3

Paper VI: Anderberg, S., Kara, S. and Beno, T., 2010*, Impact of energy efficiency on computer numerical control machining*, Proc. IMechE Vol. 224 Part B: J. Engineering Manufacture: section 5.3

Paper VII Anderberg, S., Beno, T. and Pejryd, L., 2011, *Energy and cost efficiency in CNC machining from a process planning perspective*, 9th Global Conference on Sustainable Manufacturing, St. Petersburg, Russia: section 5.3

Paper IIX: Anderberg, S., Pejryd, L. and Beno, T., 2012, *Process planning for CNC machining from a capability perspective* (submitted): section 5.2

Paper IX: Anderberg, S., Beno, T. and Pejryd, L., 2012, *Process planning for CNC machining: Results from three surveys* (submitted): section 5.1

Part II

Setting the scene of process planning

2 The basics of process planning

The chapter sets the frame of process planning work by establishing terminology employed and describing the primary process planning activities. Value and non-value adding process planning activities are defined. In relation to activities described, the constraints in process planning work are depicted. Altogether the frame around process planning work is set.

Process planning and production planning are the links between product development and production. However, there is no single definition of these terms and they differ between type of production as well as organisation. This work considers only metal cutting using CNC technology. The overall concept of process planning can be divided into many different sub-levels, where one such categorisation is made according to the constraints that restricts the possible selections during process planning (Wiendahl et al., 2007). Figure 2.1 describes the different levels of process planning, where multi-domain process is the highest level and seeks to select the most suitable manufacturing technology. Macro-process planning refers to the selection of the optimal sequence of different process steps, set-ups, and the selection of machine(s). Micro-process planning (also sometimes termed operations planning[1]) aims at optimising each individual operation regarding tool use, machining parameters and tool paths. This classification is based on ElMaraghy (2007) but with the addition of geometric and technical planning. In relation to the different process planning levels, there have been many different attempts to improve these, principally through automation. Most automation attempts have been

[1] The terminology around process planning is somewhat fuzzy, where many authors in the field do not distinguish between the different levels of process planning. Some authors make a distinction in accordance with Figure 2.1, whereas a few uses operations planning instead of micro process planning. The latter corresponds to the Swedish term 'operationsberedning' in relation to 'processberedning', which corresponds to multi-domain process planning and macro process planning. In this thesis the more general use of the term of process planning is used, where the micro level primarily is considered. However, the macro level is also included in some of the parts. Since the thesis exclusively focuses on CNC machining, multi-domain process planning is omitted here, since it is here assumed that metal cutting is the employed manufacturing technology.

[2] operation should in this context not be confused with the physical machining operation used in the previous chapter, but rather the act of transforming input into useful output (Meredith, J., R. (1992) *The management of*

aimed at the micro-process planning level. Automation of process planning and computer aided process planning are reviewed in more depth in chapter 4.

Many times a product must undergo a number of manufacturing processes, e.g. casting, forging, welding, machining and joining and assembly. Routing, sequencing, scheduling and batch sizes must be evaluated and decided upon to optimise the flow through the production plant. This is often referred to as production planning, which concerns the logistics of manufacturing a product (Groover, 2008), and is thus a higher level of planning than process planning.

In relation to process, an operation in this framework is defined as a manufacturing process of a defined geometric feature, with a specific machine, cutting tool and thereto defined machining parameters. A machining process is made up of a set of operations. The terms of manufacturing and production are here used as interchangeable terms, although differences exist in the British English and American English definitions.

Next, the act and the activities of process planning will be discussed further. As seen in Figure 2.1, making selections is a vital part of process planning work. Making a selection may appear trivial, but in this setting a selection is an activity in itself, which may incur a great deal of work in evaluating, calculating and finally making a decision that is the best possible with respect to the specific conditions.

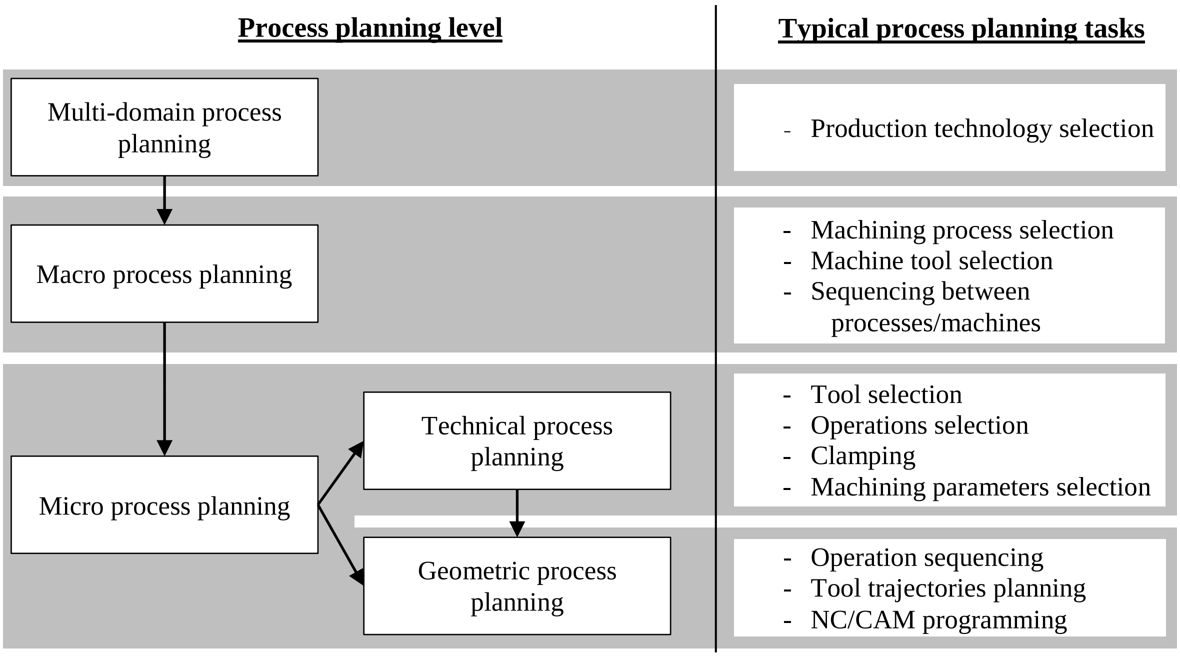

Figure 2.1 Level of process planning scope and associated process planning work tasks

2.2 The act of process planning

In short, process planning can be regarded as having the primary function of producing a process plan. The process plan can be regarded as all instructions necessary to unambiguously complete the manufacturing of a specific product. A process plan for CNC machining typically includes an NC program (i.e. machine instructions) as the centre piece and additional work instructions for operators and other involved personnel to support the machining process. If this is the result of process planning, process planning itself comprises the work activities that, through a number of selections, calculations and decisions, transform specifications and requirements into a process plan.

Wang and Li (1991) state that, in general, process planning is labour intensive, highly subjective, time consuming and tedious. Halevi and Weill (1995) claim that the process planner's main work activities roughly consists of 15% technical decision making, 40% data, table reading/retrieval and calculations, and 45% text creation and documentation. In a value adding perspective it is primarily decision making that adds direct value to the final product, while the other activities are more or less necessities for making qualified decisions in order to produce optimised machining processes. If the product value chain as a whole is then regarded, Ameri and Dutta (2005) claim that 60% of the resources is non-value adding, and only 10% is directly added value (Figure 2.2). The non-value adding activities are confined to searching, waiting and translating data, working with the wrong data, and recreating existent data (Ameri and Dutta, 2005).

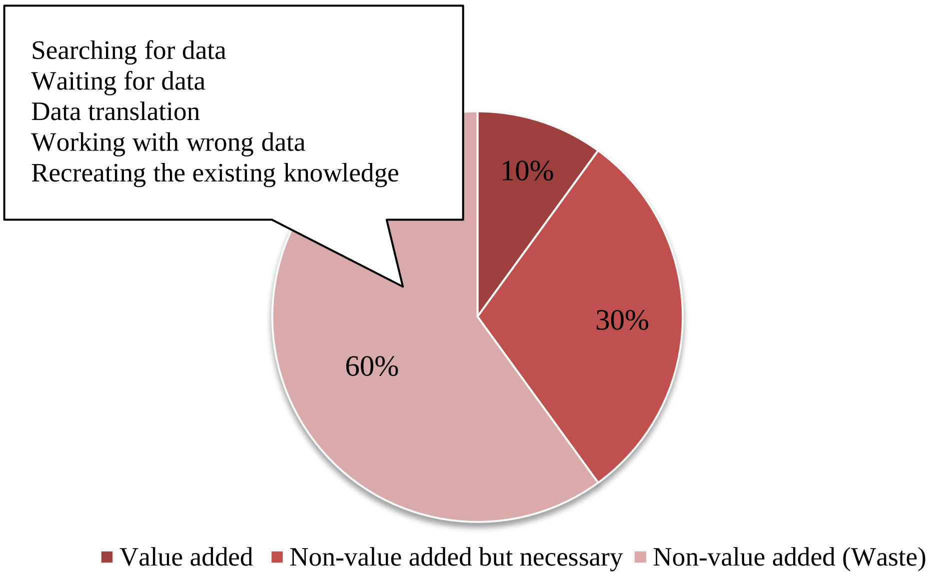

Figure 2.2 Value and non-value added work in product value chain. Source: Ameri and Dutta (2005).

In line with the above reasoning, process planning improvement aims should mainly be directed towards minimising the time and resources spent on non-value adding activities so that resources can be freed for value adding activities instead. Figure 2.3 illustrates the principal process planning function. Main value adding activities are decision making activities (i.e. concept generation and concept decisions), to which available resources should be focused, whereas the resource need for other activities should be minimised. In this perspective, data/information/knowledge retrieval and classification, which are inputs to process planning, are areas suitable for rationalisation, e.g. automation. Minimising the required time for non-value adding activities implies that more resources can be dedicated to decisions (as stated in Figure 2.3) and optimisations that influence the process planning effectiveness (i.e. machining process and the resulting product).

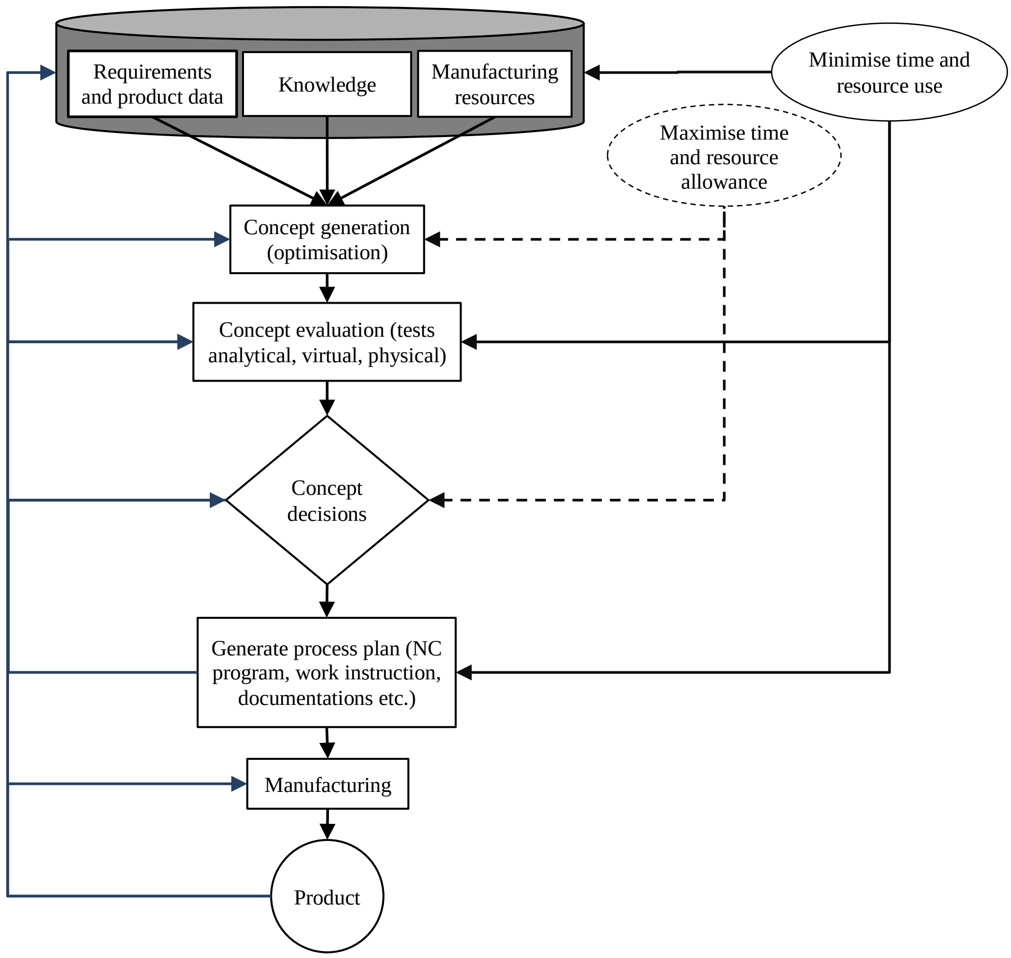

Figure 2.3 Principal flow chart of process planning, iteration steps and distribution of resource usage priorities.

Automation of process planning activities is an important part of developing efficient working methods. Automation is often thought of as being mainly about physical production, but it has a wider scope than that. Automation of manually performed knowledge work can be motivated from different perspectives, e.g. cost and lead time reduction or quality enhancements. Better process planning efficiency can be achieved with adequate process planning aids, such as IT systems, PLM systems and, CAM, but also through better and more systematic working methods. Machover (1996) claims that if the CAD design function were infinitely efficient this would only contribute to 5-10% time and cost savings in the entire engineering process. This is due to the fact that CAD design typically only is a part of the engineering work flow.

There is however often a risk when automating functions that flexibility is lost and, particularly for engineering work, that innovative solutions cannot be encouraged or achieved. It is also more difficult to automate engineering work, since the outcome often is ambiguously defined and work activities often do not follow a defined sequence (Murgau, 2009). However, automation is not the only method for achieving improvements. More systematic work and organisation of work are means that should not be neglected. This is further discussed in chapter 4. Before the use of different automation technologies to aid process planning is further studied, the main activities involved in process planning are outlined.

2.2.1 Principal process planning activities

The principal process planning activities are illustrated in Figure 2.4 and reviewed hereunder. Each activity involves various amounts of information retrieval, decisions and selections. The activities are described as being performed by a process planner – even though theoretically and practically they can be performed by a computer program. The order of the activities may differ between organisations, but roughly follows the below order. The principal activities are:

- *Interpretation of technical drawings, CAD models and other documentation of specifications and requirements* - a thorough analysis of the drawing must be carried out before the actual planning commences. The planner must regard materials (and their properties and implications for machining), geometries, features, tolerances, surface finishes and quality verification etc. Other aspects of requirements must be regarded as well, which is further discussed in section 2.3.1.
- *Processes and operations selection* - the production planner must initially make decisions about the production technology (casting, machining, welding, forging etc.) to employ. When this is done, the process planner makes decisions about the sub-processes and sequences. The selection of processes is made in accordance with the constraints as a consequence of product, manufacturing system etc. Each of the main machining processes (turning, milling, drilling and threading) comprises a variety of different operations (e.g. face milling, plain milling, form milling, grooving, facing etc.). A rotationally symmetric outer dimension can for example be machined through conventional turning or through two methods of turn-milling (orthogonal or co-axial) with a machine tool with at least four axes (Figure 2.5). A hole in a rotational symmetric part can be machined through boring, drilling, spherical milling or internal turning. The decisions are therefore not always trivial or unambiguous.

- *Machine tool selection* - the selection of the appropriate machine according to selected processes and operations. Different machine tools have different features regarding possible processes, number of axes, stability, rigidness, accuracy, power, spindle torque, work space, available speeds and feeds, number of tools, tool change times, cost rate, availability etc. Sometimes the machine choice is not given and/or the process plan should be machine-independent. Other times the freedom of choice is strictly limited and specified.

- *Blank selection* - the freedom of deciding upon different types of blanks depends largely on the production volume. For low volumes, most certainly a standard off the shelf blank should be used, which means that a great deal of material may have to be removed. With increasing production volumes, a more net shape blank can prove to be feasible. This means that less material must be removed, and hence a shorter machining process. It is also more environmentally beneficial, since less material is casted, transported and removed. Ultimately it is a matter of a trade-off between blank cost and machining cost.

- *Clamping, fixture selection/design and datum selection* - It is necessary to decide upon a way of clamping the workpiece to guarantee dimensional accuracy (i.e. tolerances are fulfilled). During machining large forces (e.g. gravity, cutting forces, vibrations etc.) act on the workpiece. The clamping and fixture must accordingly ensure that the workpiece is held in place, and that at the same time the workpiece is not damaged. The selection of workpiece positioning method is partly a matter of processes employed, the working directions of tools, the production volume in one set-up and features of the machined part. Sometimes the machine tool's own clamping system can be used, and sometimes a dedicated fixture must be used or at other times a tombstone fixture can be used to increase productivity. Dedicated fixtures must be designed for certain products, which prolong time to manufacture, and the process planner then specifies design requirements.

- *Auxiliary system selection* – In many cases the machine tool works in cooperation with other systems in the manufacturing system. These can be different cooling and lubrication systems, or automation systems, where e.g. the machine tool can be part of a production line or flexible manufacturing system (FMS) and be served by robots or other automatic equipment.

- *Cutting tool selection* - The selection of cutting tools greatly influences machining cost and time and possibilities to achieve specified dimensions and features. There is a close interconnection between cutting tool and possible machining parameters, tool paths and the mechanics of the cutting process. Tools come in different materials, coatings, and micro and macro geometries. The cutting tool has a direct relation to surface finish, power requirements and forces on the tool/workpiece and thereby influences the tendency for vibrations. The main factors to consider in tool selection are tool geometry (so that the desired geometry is generated), tool life and material removal rate (MRR). It is of interest to minimise the number of different tools, since this reduces the complexity and inventory levels, ordering costs, and the set-up time and tool change over time. Deciding upon a cutting tool is a fairly complex task, since the alternatives and combinations are almost endless. A simple search in one of the major cutting tool vendors' databases generates 100 different options of tools for a longitudinal external turning operation with a C-shape insert of 80° and an entering angle 75° for a certain type of tool holder. Consequently, it is difficult for the process planner to select the optimal tool for each operation. Moreover, the purchase strategies of the company may constrain the freedom of selection, where sometimes certain tool vendors are primarily used. Despite the almost endless possibilities and variants of cutting tools available on the market, dedicated tools must still be developed for certain applications. The process planner then specifies requirements. This is e.g. the case in gear machining.

- *Machining parameters selection* - The influence of machining parameters stand in direct relation to machining cost and time, and thus the profitability of operations. All machining processes have the fundamental machining parameters of depth of cut, cutting velocity and feed rate. However, their meaning varies slightly according to the process type. 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 of cut are important 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, and to a lower total electrical energy use.
- *Tool path generation* - This is often done in CAM or by manual offline or online NC programming and defines the trajectories of the tool relative to the workpiece. Defining tool paths is part of the overall machining strategy and is related to machining parameters and tool geometry. It is imperative to have knowledge about how certain features can be machined to avoid residual stress and burr formation. Similarly, defining machining strategies for complex geometries is important, where optimal cutting mechanics, stability and rigidness throughout the process must be considered. E.g. BLISKs require both complex axes interpolation as well as removal strategies to reduce vibrations. The machine tool sets specific constraints for the process design. The deliverable from this step is an NC program.
- *Verification of process plan* - The above decisions must be verified in some way so that the process planner can be assured that the process plan will carry out the intended production in accordance with specifications. Sometimes actual machining during production is the only test, 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 machine controller. Depending on the machining complexity and previous experiences, simulations of the basic processes, geometrical accuracy or collision detection can be performed. A process

is always subject to variations where simulations typically do not provide information on the continuous performance of the machining process. Decisions on process plan verification must consequently be evaluated. This can include various statistical methods for quality control of the resulting components, e.g. statistical process control (SPC) (Halevi, 2003). Increasing the level of confidence before actual production is an area further treated in section 5.2.3, where verification requirements in relation to data levels are discussed.

- *Work instructions and other documentation* – In addition to the general process planning activities is the creation of work instructions for the machine operators. Work instructions usually include descriptions of the handling of workpiece, tool change intervals, in-process controls and other quality control methods etc.

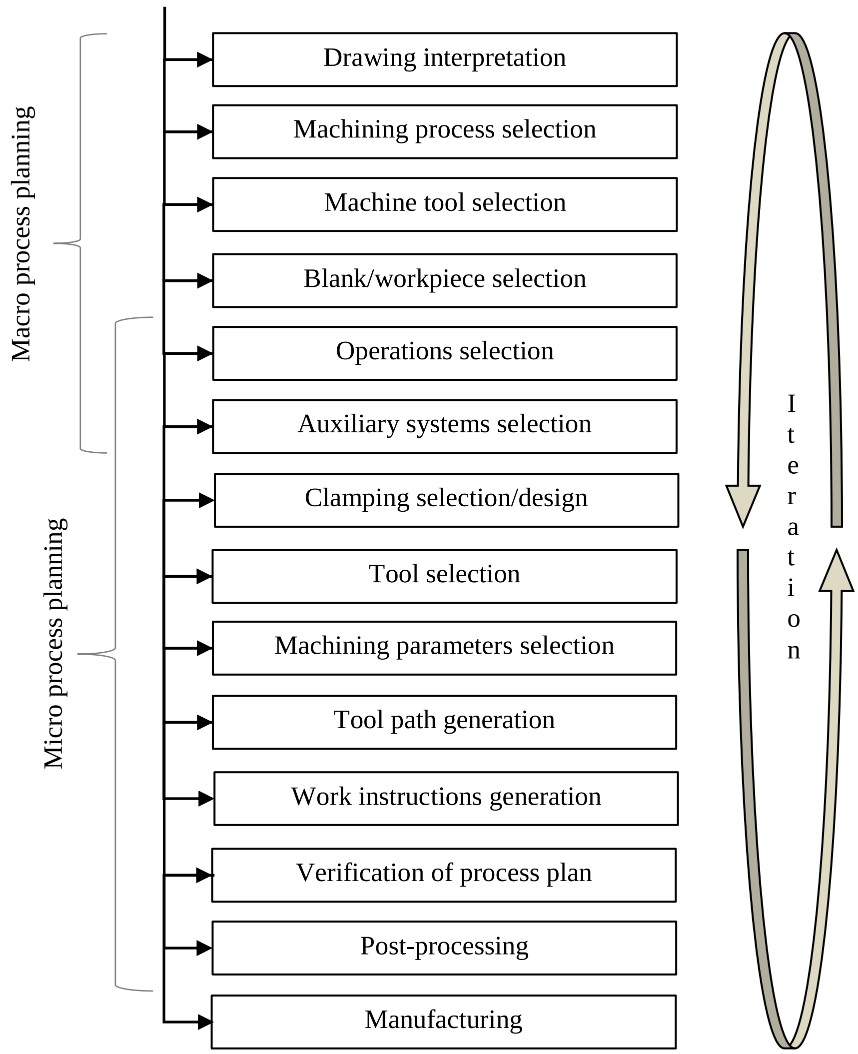

Figure 2.4 General process planning tasks, including macro and micro process planning.

In each of the activities described, information and data gathering constitute a vital part. Each of the above selections made constrains subsequent activities (and selections) and sometimes a prior selection restricts subsequent selections in such a manner that specifications cannot be met. Iteration is consequently necessary. Iterations can be regarded as reactions to previous inferior decisions but are necessary for attaining a better solution. Iterations prolong the process planning lead time and, to increase process planning efficiency, a reduction of the need for iterations is beneficial. It is in this context desirable to make correct decisions the first time. Another option is to reduce the iteration time. Simulations can here prove to be efficient tools where machining concepts can be evaluated virtually. Concurrency between activities may and should occur, which means that the above list of activities should not be regarded as a strict sequence of actions.

As described there are many different activities of process planning, and the scope differs between organisations and type of industry as well as between products. This means that process planning is not generic and must adapt to different circumstances. The role of the process planner also differs between and in organisations where different responsibilities exist or a functional vs. holistic division of labour approach can be employed. Moreover, the role of the process planner often also changes over time, with organisational strategies and type of management. The next section will briefly describe the traditional method for performing process planning work, through the use of people and principally manually.

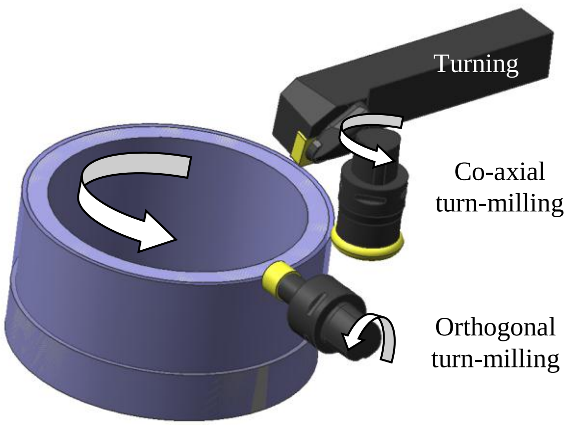

Figure 2.5 Various ways of machining a rotationally symmetric geometry.

2.2.2 Human-based process planning

Human-based or experienced-based process planning is still the default situation in the industry. It is to the major part based on manual work activities. The process planner in these systems bases decisions on knowledge from many different sources, e.g. his or her own experience as well as the organisation's experience, handbooks, tool vendors' guidelines etc. This also implies that it is the responsibility of the process planner to retrieve applicable information for the current job. The decisions made are often subjective in nature and due to the large quantity of information and data available do not necessarily generate the optimal solution to the problem.

Process planning work requires personnel with good knowledge of e.g. manufacturing processes and shop floor practices. Process planners often gain their skills and experience from the workshop as machine operators. Due to the high reliance on humans and their knowledge, process plans that are produced often lack consistency. A study by Wang and Li (1991) showed that a sample of 425 relatively simple gears resulted in 377 different process plans. 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 basic machining strategy is probably similar, but selected sub-operations or machining parameters may be different, which influence e.g. quality, cost and process rate.

A process planner must typically possess a wide variety of skills to prepare a process plan. These skills naturally coincide with many of the process planning activities stated in section 2.2.1. Parts of the skills are technical skills and knowledge about where to retrieve specific information. The proficiency to interpret and critically evaluate retrieved information is typically based on experience. These skills and the required knowledge more making effective decisions can be categorised as shown in Figure 2.6.

There are a number of inherent problems related to relying on the process planners' experience. With respect to experience, Chang et al. (1998) state that it requires a significant acquisition period, it only represents approximate not exact knowledge and it is not directly applicable to new processes or systems. Furthermore, experience is connected to individual persons, which make the organisation dependent on the knowledge of a few. If one leaves, that person's knowledge also leaves. Zhang and Alting (1993) write that one of the driving forces for developing computer-aided process planning systems in the early 1980s was that the industry realised difficulties in finding qualified process planners when many skilled and experienced process planners had retired or were close to retirement.

Knowledge repositories for human-based process planning has traditionally circled around handbooks, which can be regarded as one way of formalising knowledge, which has long been industrial practice. Larger enterprises often have internal handbooks, that have developed over the years and that collect experiences. 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 much technical literature (Halevi, 2003). However, since new tools and materials are continuously developed there is a risk for out-dated information.

Tool manufacturers also issue large amounts of recommendations for tools and machining parameters. Traditionally these data were found in catalogues, but many tool manufacturers now have online interactive machining parameter selection. The number of tool vendors and tools is vast, and it is not surprising that a large portion of process planning work is dedicated to the search and retrieval of information (see section 2.1). There exist information management systems such as CIMSource, adds functionality to the user so that tool information from different manufacturers can be combined, which leads to a lesser focus on data retrieval and a greater focus on engineering work (CIMSource, 2011; Nyqvist, 2008). Tool vendors can also have more direct interaction with customers through visits and direct communication. It is not unusual for a tool vendor to 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 to give recommendations in exchange for purchase orders. This can be considered one way of outsourcing some of the process planning work activities.

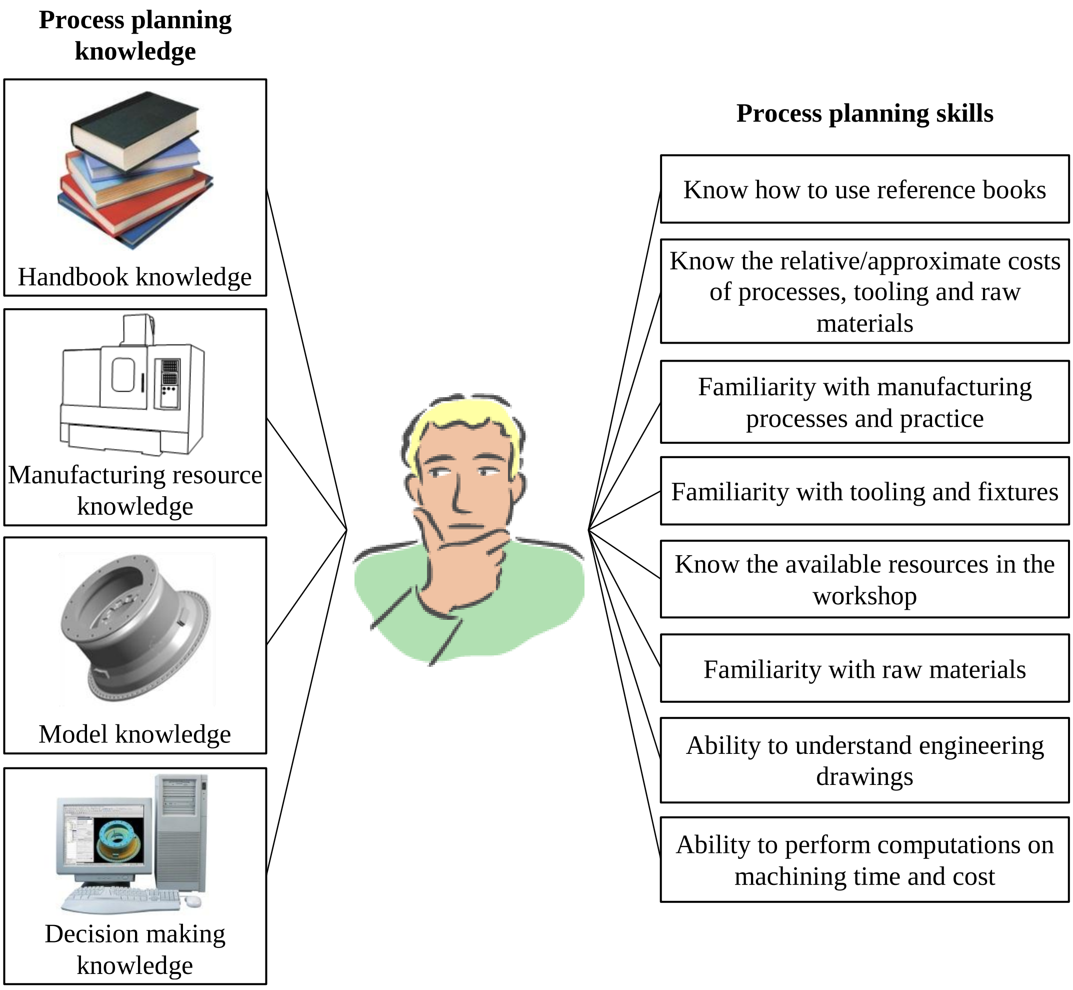

Figure 2.6 Human-based process planning knowledge (Jia et al., 2008) and skills (Chang and Wysk, 1998).

2.2.3 Optimisation

In general, the purpose of the optimisation process is to determine a solution to a problem so that the specified goals and objectives are most closely achieved. In any system, there exists a set of different concepts that fulfil specified goals, objectives and criteria in different ways. It is therefore important that the company have specified and quantified goals, so that the system is optimised according to the actual objectives. The optimum solution is usually defined as the technically best solution that is achieved without any trade-off between goals and objectives (Meredith et al., 1973). However, since the goals, objectives and criteria inevitable conflict, the engineer or process planner must make trade-offs in the optimisation process. Meredith et al. (1973) state that there are three principal types of optimisation methods - analytical, combinatorial and subjective. Process planning characterised by major parts of human interaction leans heavily towards the subjective form of optimisation, where the many optimisations take place in the head of the process planner. Much work has been devoted to finding ways to formalise the knowledge, designing decision aids and designing intelligent algorithms to imitate and outperform the human process planner in parts or all of the process planning function. However it has proven to be difficult, which will be discussed later in the thesis.

A process planning function that can make better decisions faster is the aim of most improvement measures and it imposes requirements on the design of the process planning function and its relation and interface to other company functions within and outside of the own organisation.

The simpler form of process planning optimisation occurs when machine tools, cutting tools, fixture and product specifications are given. It is then an issue of using given constraints and doing so in an optimal way in accordance with requirements (Grieves, 2006). When any of the above constraints are open for modification, such as when new cutting tools are introduced to the market, investments in new machine tools are possible, or there is new fixture design or change in product specifications, the complexity level of process planning increases as a consequence. The level of complexity of parameter optimisation in the simpler case is already high, where 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 satisfies the given requirements (Grieves, 2006). Human beings are not well equipped to perform those searches and optimisations. However, it is often the case that information and data retrieval along with the combination of it into concepts (i.e. the optimisation) is highly manual work. Together with the retrieval of correct information and having effective optimisation methods, constraints influence the possibilities to optimise process plans.

2.3 Constraints

Understanding how different factors constrain process planning is vital to better assess deficiencies that follow problems in process planning and deficiencies caused by other factors than process planning. When process planning performance is dissected it is sensible to make a distinction between external and internal constraints for process planning. The external constraints are here defined as those demands and requirements that constrain the process planning function but cannot directly be influenced by the process planning function itself. The external constraints largely consist of customer demands, i.e. speed, time, quality, cost, as well as environmental demands. They also include standards and regulations, and the properties of the manufacturing system. The internal constraints refer to those factors that constrain the process planning function and can be directly or indirectly influenced by the process planner. To a large extent, and this is reviewed in more detail below, the constraints are related to the constraints that process planning decisions render. These are primarily related to technological and knowledge aspects of process planning and CNC machining.

Figure 2.7 illustrates the different constraints in relation to process planning. As is seen, some of the constraints are difficult to categorise, since they are dependent on the relation between business partners and the organisation of the company. The division between the two types of constraints is not sharp and it can be disputed whether or not custom demands are receptive to process planners' actions. In reality it is based on the individual case and organisation.

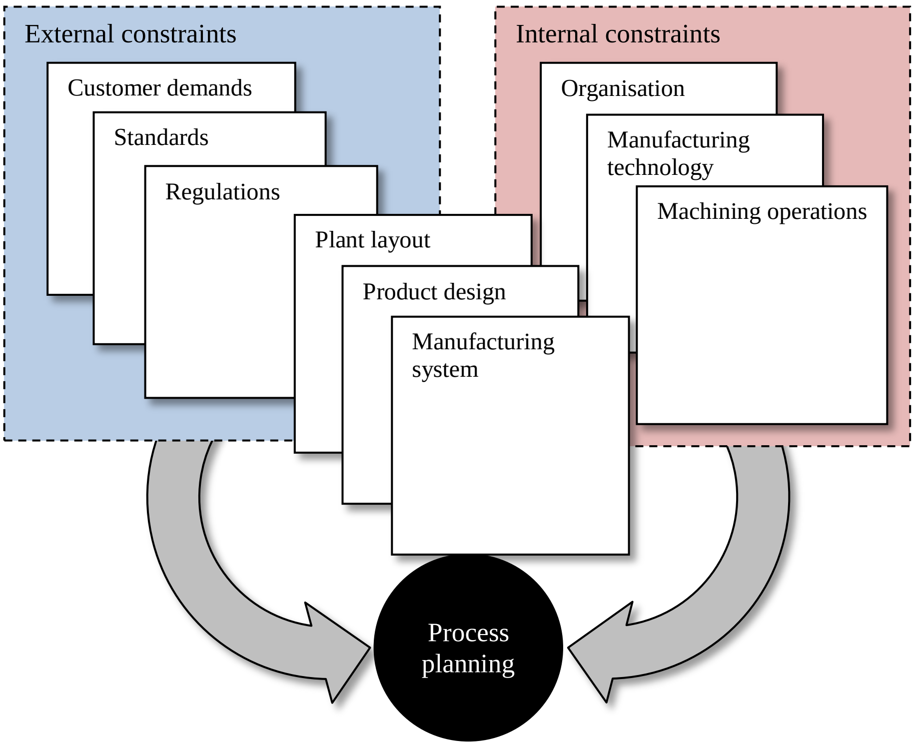

Figure 2.7 External and internal constraints in relation to process planning.

2.3.1 External constraints

Customer demands mainly constitute external constraints, which a company must be able to act on in order to be competitive. Regulations and standards restrict process planning activities or require certain activities and/or documents to be completed. Many companies are certified according to quality management standard ISO 9000 and environmental management standard ISO 14000, which also impose restrictions on process planning.

The constraints are influenced by the individual company's position in the supply chain. Many metal working companies are suppliers or sub-suppliers in the supply chain, which often means that they do not have direct contact with the end customers. The supplier may or may not have its own component design responsibilities, which influences how constraints apply to the supplier at large and process planning in particular. If the supplier does not have design responsibilities, there are fewer possibilities for making design changes for increased manufacturability.

Whether or not there is a longstanding relation between manufacturer and supplier also influences process planning constraints and the possibilities to ensure high process planning efficiency. The level of integration between business partners influences the information exchange, e.g. product specifications, drawings and CAD models and overall system integration.

The product itself is 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 only a matter of mouse clicks to define the same 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 (fixtures and clamping) to be machined efficiently, thus making tool selection more intricate.

The automation level of the production system, where CNC machines constitute a part that interfaces with automation equipment (conveyers, feeder, robots etc.), can be regarded as an external constraint. If CNC machines are part of a fully automatic production line or FMS then this implies that the machining process must be operator-independent. Under those circumstances, there is no possibility to use any operator; thus the machining process must be capable and robust without manual input. Such requirements impose different demands on process planning. The situation can be described bottom-up, from a process capability perspective and the possibilities for automation (see section 3.2.1).

Raising customer awareness of environmental issues puts pressure on all company operations to adopt more environmentally conscious thinking. In the manufacturing situation this can be manifested in the form of e.g. usage of environmental standards and black listed substances. These actions directly constrain the process planning work. Other means include internalising external environmental effects, where the company can set punishment costs (based on non-market prices) on certain methods or substances and thereby limit its use. Carbon dioxide emission cap-and-trade schemes (e.g. the EU ETS) are examples of this method, but on a global scale. Anderberg et al. (2010) concluded that the current price of the EU ETS is too low to significantly influence process planning decisions. Internalising external constraints can however be a method for imposing "soft" constraints and transferring them to the internal constraints; hence it becomes a cost parameter among other costs.

2.3.2 Internal constraints

Decisions made during process planning most often influence subsequent process planning activities – the introduction of internal constraints. This means that, if constraints imposed earlier in process planning cannot be transcended, 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. If one parameter is changed, the prerequisites of other parameters are changed as well. This has the consequence that the complexity level of process planning increases. Furthermore, a part can often be machined in multiple ways, which is illustrated in Figure 2.5 for machining of an outer cylinder diameter. Often, optimisation algorithms focus on the machining parameters as the principal optimisation factor. However, if the chosen machining process is inferior to other processes, the result will never be globally optimised. It is therefore important to initially ensure that the most appropriate machining process is selected. The selection of process constrains the possible machine tool selection, i.e. such constrains as whether if one or several machines are needed, there is a need of re-clamping, tool magazine size etc. Often it is specified which machine shall be used; then it is the machine that constrains the machining process selection.

Today, many different types of machine tools exist, where multi-task machines, mill-turns, turn-mills and machining centres all denote machines with more than one machining process option. Consequently, the specific machine tool selected renders a set of constraints that must be considered in subsequent process planning steps. The cutting tool selection significantly influences the possible machining parameters. In turn, machining parameters considerably influence the machining process by having a continuous and normally wide span of possible parameter combinations (Figure 2.8). The machining parameters directly correlate to MRR, consequently machining cost and time. Machining parameters are also closely correlated to tool life, and the decision between material removal rate and tool life is the major optimisation to be made for a specific machining operation. Machine power often sets the upper limit for possible machining parameters if tool life is not the limiting criterion. Power and machining time, which are both consequences of machining parameters, govern the energy use of machining processes. In turn, energy use has implications for the environmental performance of the machining process (see section 3.3.2).

The clamping system has a 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 MRR) also imposes higher forces on the workpiece. Clamping thereby indirectly influences machining time/cost and quality. The attempts to achieve high rigidity sometimes restrict the machining process, so that reachability is hampered or that different fixtures are needed for different operations. In the optimal case, no re-clamping is needed to perform all machining operations. This reduces the likelihood of errors and geometric deviations related to workpiece positioning. It is advantageous if standard fixtures can be used, since fixture design is typically costly and time consuming, thus prolonging lead times.

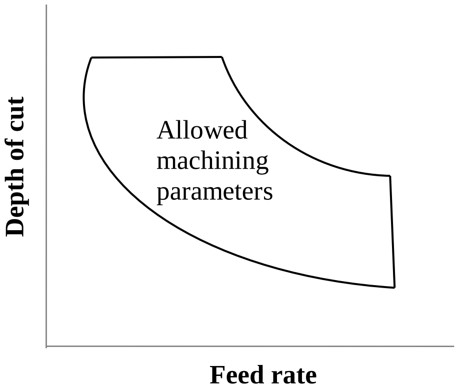

Figure 2.8 Permitted combinations of feed rate and depth of cut of an arbitrary turning tool.

2.3.3 Summary boundary constraints

The various constraints can be summarised schematically (see Figure 2.9). The possible operational parameters can be found if all restrictions are put together. However, under certain circumstances, it may not be possible to find a viable process window. This can be the consequence when recommended and selected machining parameters result in a process rate that exceeds the specifications of the machine or the cutting tool. There can also be product requirements that do not allow tool changes during the machining of a certain feature (external product requirements), since it would interrupt the cut and cause surface integrity problems. Figure 2.9a illustrates a process window where the manufacturing organisation has experience. However, it can also be seen that there are domains where the organisation currently has no knowledge (experience) and where there are potential benefits (e.g. cost or time reductions) to be gained if these domains are investigated further. If a process window is not found under the current circumstances, any of the factors affecting the constraints must be revised (e.g. a different machine, tool or revised design or manufacturing requirements), which is the situation illustrated in Figure 2.9b.

In any of these two cases it is vital to have an effective methodology that brings knowledge about the unknown situations closer to a machining solution. This is further discussed in section 5.2.4.

This chapter established the basics of process planning, which should be regarded as a foundation for understanding the great complexity and variation of process planning, where this thesis made a distinction between internal and external constraints. These aspects constitute important areas for the underlying reasons why it still today is difficult to find efficient and effective methods to perform process planning and hence still an area under research. The next chapter will move into the area of understanding what process planning is attempting to achieve in terms of objectives. In relation to the objectives, process planning performance, different dimensions of performance and ways to quantify and measure performance are reviewed.

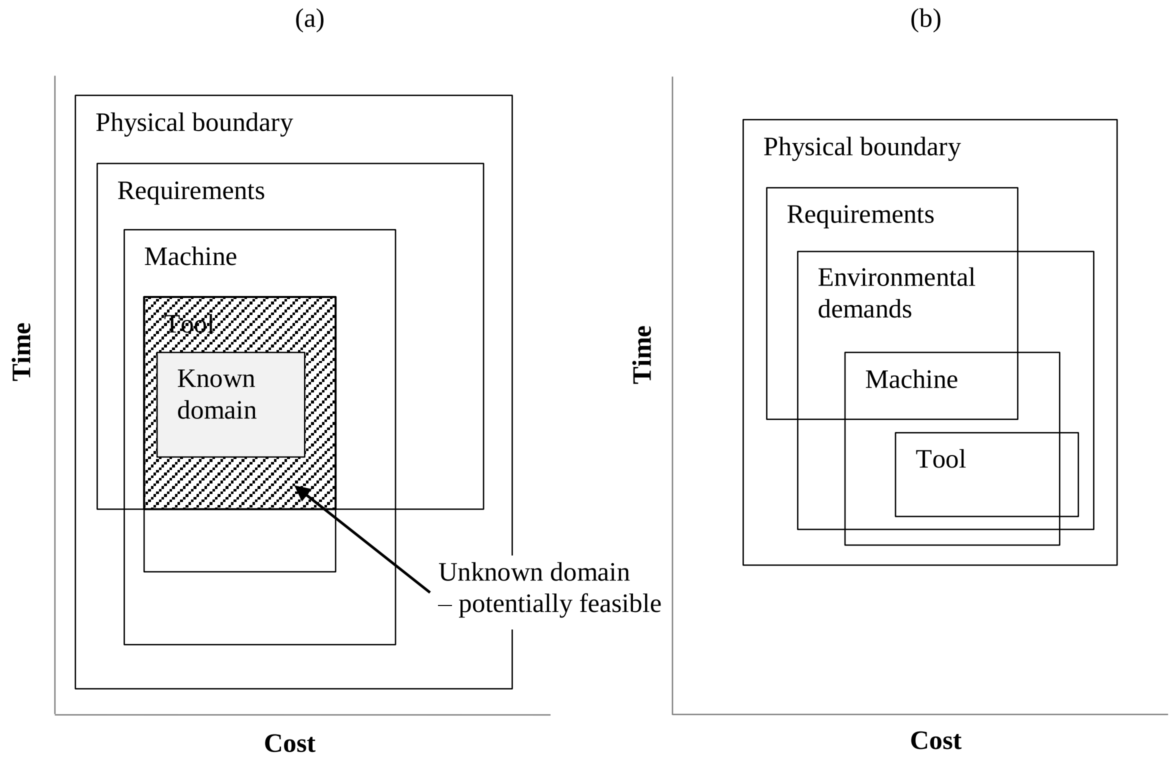

Figure 2.9 Process windows where (a) illustrates a case where the tool dictates the possible process window and where unknown domains of the process window indicate potentially feasible domains. (b) illustrates a case where the current configuration does not fulfil internal and external boundaries. Hence a process window is not found.

3 Process planning objectives and performance

The objectives of competiveness and performance are first outlined in the chapter. Thereafter the relation between production cost and process planning cost is laid out and discussed. The distinction between process planning efficiency and effectiveness is also established. The increasing importance of the environmental performance of machining processes and process capability are given particular attention as factors for effectiveness.

In general, there are a number of dimensions that influence all manufacturing organisations and that are fundamental for understanding the performance of company operations[2]. The priority between these performance objectives has shifted in a historic perspective and does so continuously. The traditional ones are cost, quality, speed, dependability and flexibility as defined by Slack et al. (2004), but environmental impact should also be included (since it cannot directly be incorporated in any of the other dimensions, although attempts have been made to internalise environmental impacts as cost surcharges). The environmental impact of products has had an upsurge in consumer awareness during the last years, which means that environmental performance consequently qualifies as a factor of competition. As such, environmental performance has the potential to increase profit margins (through higher pricing), sales, market shares and market opportunities (Rao and Holt, 2005). Which of the performance objectives are most important is a matter of competitive positioning of the company and the customer base, although all dimensions are important to some extent (Hallgren, 2007).

Performance objectives can be defined on different levels in the company and supply chain, which have implications for the scope of objectives. For example, overall cost reduction objectives of the supply chain can be translated into quantifiable lead times of the employed machining processes, which in turn influence process planning decisions. In this thesis, it is essentially the influence that the machining and process planning level

[2] operation should in this context not be confused with the physical machining operation used in the previous chapter, but rather the act of transforming input into useful output (Meredith, J., R. (1992) *The management of operations: a conceptual emphasis*, 4th ed. ed, John Wiley & Sons, Inc.,).

has on the performance objectives that are considered. Overall objectives can be transformed into specific objectives of the outcome of process planning (machining process and product), e.g. total machining cost, lead time, product quality, process capability, energy use etc.

The performance objectives and how these are influenced by process planning are briefly outlined:

- Cost is influenced by the decisions made during process planning, since tooling, machining parameters, machine selection etc. all influence total machining cost, mainly via the process rate, i.e. the speed of the machining process. Cost is also influenced by tool wear, energy use and monitoring need.
- The speed of the machining process is influenced by process planning decisions in a similar fashion as is cost. The overall speed of product realisation is partly dependent on the lead time of process planning. Speed and cost are interrelated, although the two do not necessarily coincide.
- The environment is influenced in the same way as are cost and speed, where they are all interrelated with and subject to process planning decisions and the manufacturing technology.
- Quality is influenced by process planning, where e.g. surface finish is directly influenced by machining parameters and tool selection. Machining dynamics, such as the tendency for chatter, tool wear, workpiece and tool deflection, also influences the dimensional accuracy.
- Flexibility is becoming increasingly important, since a key to creating products for a diversified customer base is a short development cycle (Chryssolouris, 2005). ElMaraghy (2006) defined ten aspects of manufacturing flexibility, where e.g. machine, process, product, volume and control flexibility all are influenced by process planning. To a large extent it is a matter of enabling effective management of new and existing knowledge.
- Dependability can be regarded as the reliability of the manufacturing system to produce according to specifications. A robust process is desirable, and the design of machining processes for increased process capability is one method for improving dependability.

To the above adds the aspect of time to reach target values, thus time to meet specified quality level, production lead times etc. Still, the management of a company is based on economic considerations where the above factors are quantified and translated into economic terms. This means that total cost and revenue are what ultimately counts – that cost objectives are met but which are directly or indirectly influenced by the above. Therefore a discussion on the relation between process planning cost and resulting total machining cost is vital.

3.1 Process planning cost versus production cost

Engineering work such as product development and process planning may only comprise a smaller part of the direct product cost compared to e.g. cost of material and manufacturing. However, as an enabler for efficient production of demanded products, engineering work greatly influences the total product cost. More time and resources invested in process planning will influence manufacturing time and cost and thereby total product cost. Devoting additional time and resources to product design and process planning should not only result in better performing products during the use phase, but also more producible products and better production performance. Spending additional resources on ensuring efficient production may be less important for low volume manufacturing but this gains importance with increasing production volumes.

Similar reasoning is applicable for manufacturing high value goods, long production lead times and relatively low production volumes, as in e.g. the aerospace industry. Aerospace engine components typically require some 20 hours of machining time - often much more. A complete engine assembly consists of many such components and thus in total exceeds many hundreds of machining hours. Since it is not uncommon that engine concepts in aerospace have lifetimes of 20 years, even a reduction of machining time by 20 minutes (which in proportion to the total production time is relatively limited) results in substantial accumulated savings over time.

Figure 3.1 illustrates the relation between machining time and process planning thinking time. Spending additional time and resources on process planning generally implies decreased machining time. In these circumstances, time can easily be translated into cost. Reduction of machining cost can from this perspective be regarded as coming to a price of increased process planning cost.

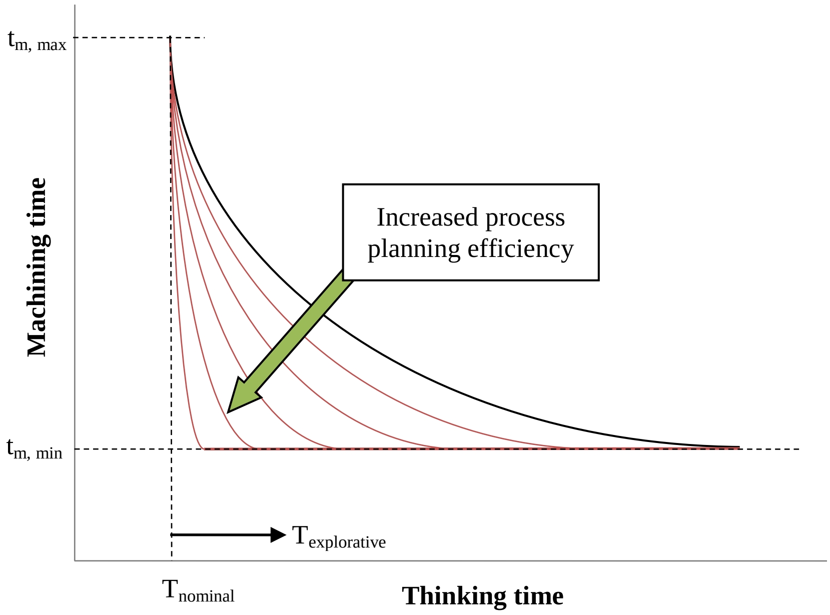

Figure 3.1 Machining time as a function of process planning thinking time. Adopted and modified from Halevi and Weill (1995).

At times, machining time savings can be achieved with relatively little additional planning time. To do this, it is vital to have good process knowledge so that planning time is given to areas where effects give the most return. Once the "low-hanging fruit" has been harvested, additional time spent on explorative process planning activities may not result in as significant machining time reductions. Various methods exist for achieving maximum effects on reductions of machine time, and this is the topic of chapter 4. Figure 3.1 illustrates these ambitions for improving efficiency.

Consequently, the ratio between thinking time and machining time (or cost) should be assessed to investigate from a cost perspective when it is beneficial to spend additional and explorative resources on process planning efficiency and when it is not. With inspiration from Halevi's (2003) reasoning on process planning cost, the following part has evolved. The cost of process planning (C_{PP}) versus the cost reduction in machining time is basically the marginal cost for reducing the machining cost (C_M). Simplified, this can be illustrated in the formulas that follow and by Figure 3.2. The cost for process planning activities and machining operations can be formulated as in equation 3.1 and 3.2 respectively.

$$C_{PP} = L_{PP}(T_{nominal} + T_{explorative}) \tag{3.1}$$

$$C_M = K_M \cdot N(T_M - \Delta T) \tag{3.2}$$

Where:

C_{PP}	Process planning cost
L_{PP}	Process planning cost rate
$T_{nominal}$	Nominal process planning time
$T_{explorative}$	Explorative process planning time
C_M	Total machining cost
N	Production volume
T_M	Total machining time
ΔT	Machining time savings due to explorative process planning time ($\Delta T = t_{m,\,max} - t_{m,\,min}$)
K_M	Machine operation cost rate (including operator cost)

The total machining cost includes the machine operation cost rate (K_M) as well as the cost for auxiliary equipment and operators etc. needed in the process. As is discussed in section 3.2.1 the need for appraisal equipment and operators is governed by the intrinsic process capability, which to some extent is a process planning issue. Hence process planning not only influences ΔT but also K_M.

To make additional process planning activities economically motivated, one seeks to keep the marginal process planning cost lower than the achieved machining cost savings. This can be expressed as in equation 3.3.

$$L_{PP} \cdot T_{explorative} < K_M \cdot N \cdot \Delta T \tag{3.3}$$

As seen in Figure 3.2 and equation 3.3, a higher process planning cost can be economically motivated with increased production volume (or rather total machining time). $T_{explorative}$ in relation to $T_{nominal}$ should be understood as the additional time required for refining a process plan in order to reduce time and cost or improve output quality and process capability for the machining operation. $T_{explorative}$ incorporates simulations, analyses and tests etc. that are necessary to enhance the knowledge about a certain situation in order to produce a better performing machining process. It is essential to be aware of the potential benefits and the magnitude of different costs in order to make effective decisions about where the minimal $T_{explorative}$ will result in the maximum ΔT.

It should be advantageous for a company to be able to assess these costs at least on a basic level when quoting on a job or making internal prioritisations between different jobs and activities. It can also be one of the methods for assessing process planning improvement needs and identifying where investments will be most effective. The next section will move further into the area of process planning performance and indicators of performance and why it is important to monitor performance.

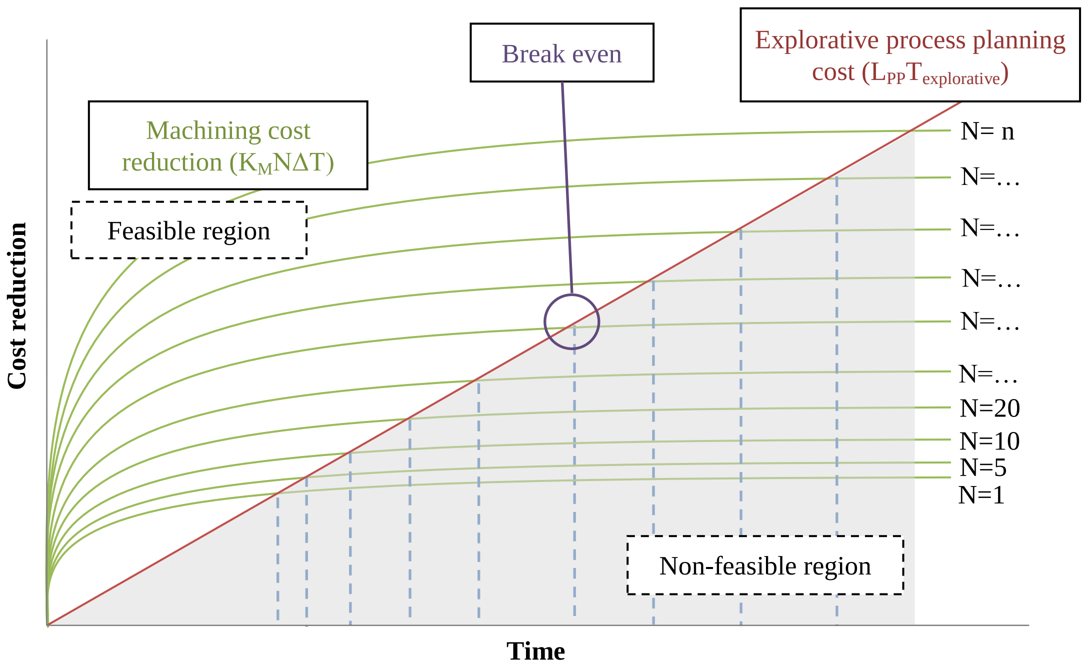

Figure 3.2 Explorative process planning cost versus machining cost reduction.

3.2 Process planning performance

Quantifying the performance of process planning is not an easy task; there are many risks of defining sub-optimal performance indicators. Mainly focusing on the efficiency of process planning and strictly considering resource use and lead times will most certainly lead to an overall low performance of the manufacturing system in the long run. This is obvious, because the result of process planning is essential.

Efficiency can be regarded as the quality or degree of effective operations as measured against cost, resources and time (NN, 1995). In traditional work studies and Scientific Management, it is principally the efficiency of work that is considered. Efficiency is related to the concept of total productivity. Total productivity is defined as the product of three loss factors - *method, utilisation* and *performance* (Saito, 2001). Method losses are consequences from the use of inefficient methods, which imply that excess personnel and machinery are needed. Performance losses follow due to low performance of personnel and equipment and utilisation losses come as a consequence of underutilisation of personnel and/or equipment. This means that the way to improve productivity is by improving one, two or all three factors. In this thesis the method factor of process planning is the primary field of study. Focusing on the method factor is defensible, since it is the single most important factor and can have a tenfold influence on productivity in manufacturing (Almström and Kinnander, 2008). Although total productivity was originally developed for manufacturing, it is also applicable for analysing engineering work such as process planning. Many of the most common performance indicators are not subject to a standardised definition but have several definitions. This is particularly the case for productivity (Murgau, 2009; Tangen, 2007) and is one of the reasons why this thesis principally uses performance, efficiency and effectiveness in their arbitrary form. The lack of coherent definitions of performance indicators implies difficulties in unambiguously communicating performance to involved parties.

The effectiveness of product development at large (including process planning) is important. An organisation or operation that does not provide a service or product that meets expectations is of very little value altogether. Drucker (1999) states that "Effectiveness is the foundation of success - efficiency is a minimum condition for survival after success has been achieved. Efficiency is concerned with doing things right. Effectiveness is doing the right things." Effectiveness can be defined on many different levels, where the level of the utmost importance is the production of goods that fulfil customer needs and expectations. This is not a process planning objective, but rather a management and product development objective. However, overall organisational effectiveness is omitted here and the focus is on process planning effectiveness; thus only factors influenced by process planning decisions are considered. This implies that, in order to define process planning performance indicators, intangible customer demands must be translated into tangible requirements as a basis for performance indicators, which relates to production and products. A common production performance indicator is overall equipment effectiveness (OEE), which is a product of availability rate (A), performance rate (P) and quality rate (Q) (Slack et al., 2004).

Each of these factors is to some extent influenced by process planning decisions, but also by many other factors, which makes it an intricate task to unambiguously pinpoint process planning effectiveness from an OEE value. Since 1988 when Nakajima presented the idea of OEE, other researchers and organisations have presented alternative definitions on A, P and Q (De Ron and Rooda, 2006). This means that an OEE value may have different content and meaning depending on the organisation.

In relation to effectiveness, it is relevant to discuss what a good process plan is. Scallan (2003) states that a process plan generates a product manufactured to the correct specification, at lowest possible cost and completed on time. Such a definition of a good process plan is arbitrary in nature, but is it possible to unambiguously define what a good process plan is? For a given product, specifications can be defined unambiguously, as well as a specific time when product is to be delivered, hence finished in production. However, minimum total cost is more difficult to define. For a specific product, manufacturing situation (machine, tools, operators etc.) and time it may be possible to derive at least a theoretical minimum total cost. However, with the development of technology, the map is continuously redrawn, where new cutting tools and machines changes what is possible to achieve. What was state of the art 10 years ago, is not necessarily state of the art today. It is therefore difficult to state globally valid minimum total cost criteria. If we accept that at least a local optimum must exist for a given manufacturing situation and time then what prevents us from arriving at an optimal process plan? Firstly, it is a matter of knowledge (process planners' and organisation's knowledge). Secondly, available time to allocate to the specific task and thirdly, it is dependent on the available resources (for process planning and manufacturing).

Figure 3.3 illustrates how efficiency and effectiveness of process planning are defined and used in this thesis. Efficiency in this context is the amount of resources and time required to produce a process plan. Effectiveness on the other hand is how well a process plan renders production and products that correspond to specified requirements. To summarise the above aspects of efficiency and effectiveness of process planning:

> *The optimal process planning function uses a minimum of resources during as short a time period as possible, and its outcome in terms of a process plan results in production of products that meet or exceed all specifications at minimum total cost and completed on time.*

The two indicators of process planning effectiveness that this thesis focuses on, which are increasingly important, are process capability and energy efficiency of CNC machining from the process planning perspective. It should be noted that when the performance term is used here, it is not specified whether it is efficiency, effectiveness or both that is being regarded.

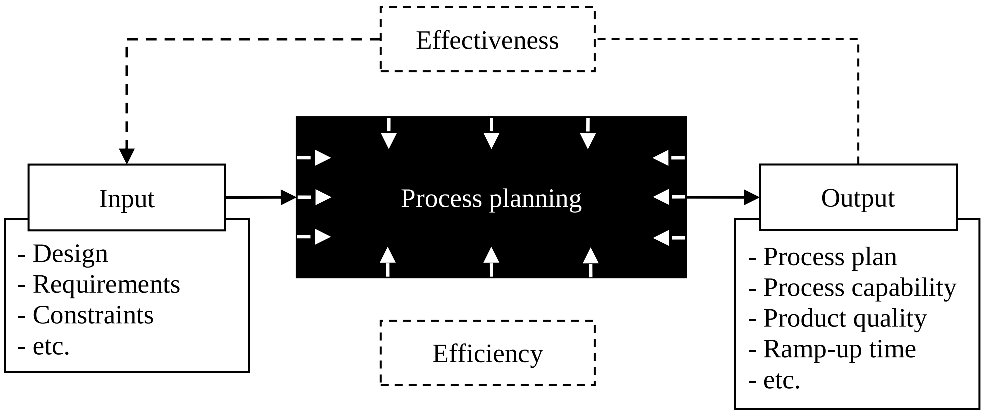

Figure 3.3 Process planning efficiency and effectiveness.

3.2.1 Process capability

It is common to refer to the robustness and capability of machines and processes, but the terms often have slightly different implications between organisations and individuals. Different scholars also define the terms slightly different, as for example:

> Montgomery (2009): "A robust process is insensitive to external sources of variability."

> Juran (1989): "Process capability: the inherent ability of the process to carry out its intended mission."

The definition of capability used here combines the two above definitions and includes the result of the process, which is implicitly stated in Juran's *mission* term. A capable process is thus defined as:

> *A capable process is robust to external sources of variability so that the intended task is carried out and an outcome (product) according to specifications is produced.*

The use of capability studies and performance data measurements from production is not new. However, it was not until the 1980s that statistical methods for measuring capability commenced on a major scale and, since then, a great deal of research has been done in the field (Deleryd, 1998). Today many companies use statistical process control to some extent, but the scope and use differ between companies. The introduction of Six Sigma in the 1980s was a conceptual approach to decreasing the proportion of products that do not meet specified tolerances.

Six Sigma underlines the use of process capability indices (PCIs)[3] to monitor and communicate capability. The most common PCIs are C_p and C_{pk}. A PCI is an aggregate of process statistics combined into one figure. These indices were designed to be positive values, where higher values are better. A value of 1.0 corresponds to three sigma (standard deviations), and 2.0 corresponding to six sigma. The most basic of the PCIs is the C_p value, which compares the specified tolerance limits to the processes' standard

[3] Also denoted PCRs (Process Capability Ratios) in some literature.

deviation multiplied by six to give the size of six standard deviations (equation 3.4). This index does not regard process centring and can give high values for processes that are off-centre in comparison to nominal specification; hence an alternative index is often used - C_{pk}. This index compares the tolerance limits to the process average in relation to the standard deviation (equation 3.5). The PCIs covered here assume normally distributed data and processes in statistical control. Other measures exist and are used, but here the scope is limited to C_p/C_{pk}.

$$C_p = \frac{USL-LSL}{6\sigma} \tag{3.4}$$

$$C_{pk} = Min(\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}) \tag{3.5}$$

Capability can be described on different levels. A common division is between the machine capability and process capability, where the machine capability only takes into account the capability of the machine itself, not what it is capable[4] of producing in an industrial setting. This measure mainly refers to the accuracy and repeatability of the machine. In a CNC machining situation, it is thus a measure of the machine tool's ability to machine parts (Larsson, 2002).

In the industrial environment there are many factors that influence the process capability, e.g. input variations, environment and process dynamics etc. Different methods exist to overcome machine and input variations to achieve an overall robust process (Figure 3.4). The machine itself can have a high C_{pk}, but the input parameters show considerable variation, thus resulting in a process that is not capable and robust altogether. The principal methods for overcoming this problem are:

1. Decrease the variation of input (e.g. upstream quality assurance programs).
2. Optimise the process parameters so that the variations of the input can be mastered.
3. Manage the variations in input by introducing appraisal activities such as in-process inspection and control (manual or automatic).

[4] A capable process is here defined as a process that at least satisfies a stated PCI-value.

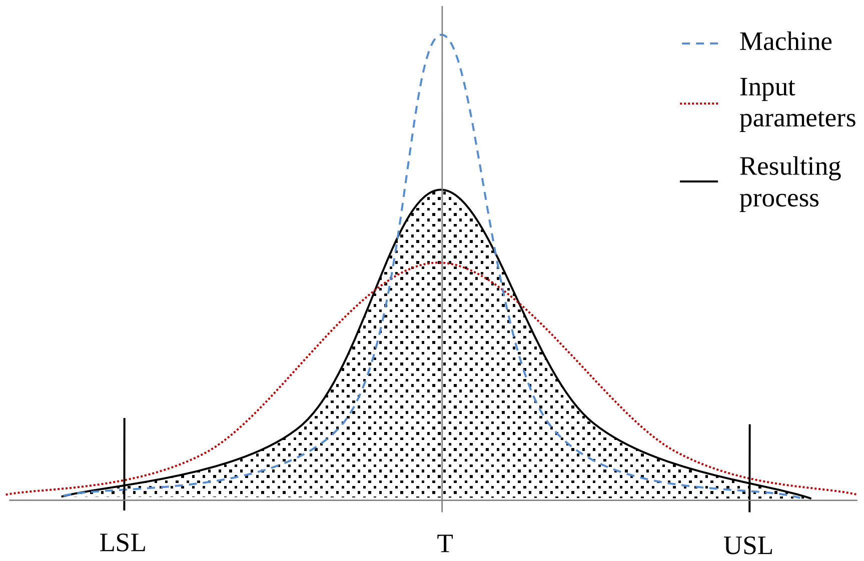

Figure 3.4 Variation of input, machine and the resulting process.

The capability of the process influences the possibilities for automation. A manual machining approach is necessary when the capability of the machining process is relatively unknown and/or the variation in outcome is substantial. This means that each operation must be verified, i.e. measurement of the machined feature by the machinist and subsequent operations are adapted to the outcome of previous ones.

The next automation level can be achieved when process capability knowledge exists and the intrinsic[5] capability is low; there a completely hands-off approach to the machining process is not possible. For these machining situations, probing and due compensations must be made for each machined part. This is often referred to as closed-loop machining.

A higher level of automation is the case when the process is intrinsically capable, which implies that no interaction during machining is necessary in order to produce in accordance with specified requirements (Figure 3.5). An analogous reasoning can be found in the early attempts of mass production with the introduction of the continuous assembly line in 1913 by Henry Ford. Womack et al. (1990) state that the continuous assembly line would have been impossible without ensuring that the parts delivered to the line were within specified tolerances – and that this was Ford's real innovation. The prior traditional approach was to manually adjust and fit each individual part to one another before assembly.

In general, the closer to passive automation a production process comes, the better, since it reduces the complexity level of the system and reduces the need for appraisal costs. It can also be argued that these are non-value adding (or indirectly value adding) activities, since no material is being removed. However, in many situations, it is not possible to produce without active appraisal activities.

[5] An intrinsically robust process is robust without appraisal aids during manufacturing.

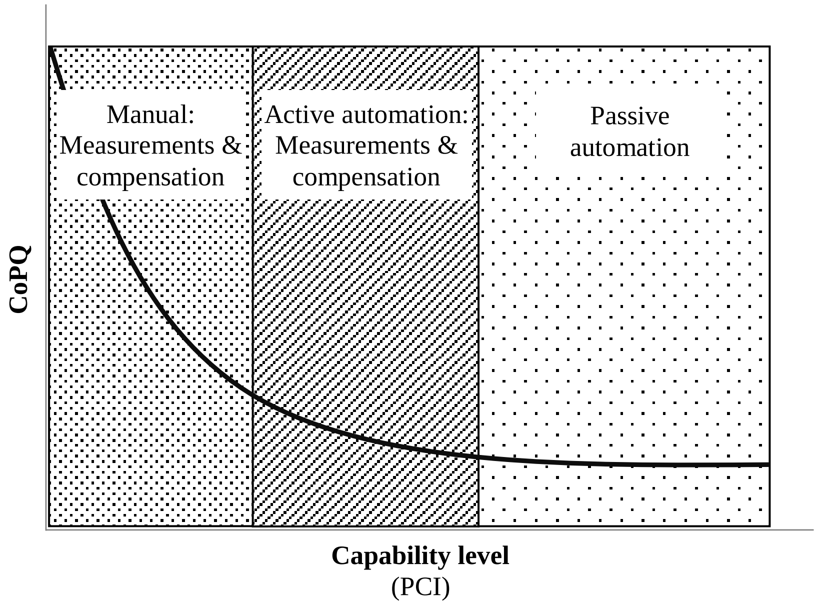

Figure 3.5 Process capability and the possibilities for automation.

3.2.2 Confidence intervals of capability indices

The above reasoning relates to actual production. However, from a process planning perspective on process capability, it is vital to be able to assess the capability of new processes before these are implemented in production. When planning a new machining process, it can be decided that the designed machining concept should be tested in pilot production or through lab oriented machining tests before actual production commences. Either way, the reliability of these tests must be evaluated from a long term production perspective. If only a small sample is evaluated and the outcome is acceptable, i.e. it produces according to a defined minimum C_{pk} value, the process planner must evaluate the long term effects. If decisions are based on test samples, the actual process capability during production can differ considerably. It is therefore necessary to calculate PCIs as confidence intervals when making tests or for low production volumes. Figure 3.6 shows a plot of C_{pk} values expressed as confidence intervals for different sample sizes. The C_{pk} confidence interval equations[6] used are given by Montgomery (2009). In a series of ten test runs, where a C_{pk} value of 1.33 is achieved, the C_{pk} value in actual production may vary between C_{pk} 2.0 and 0.7 (a value under 1 is often insufficient). The solution is either to carry out more repetitions to increase the sample size, and consequently narrow the confidence interval, or to improve the process so that the C_{pk} value is enhanced. Thus the lowest value is raised but the width of the confidence interval is kept constant.

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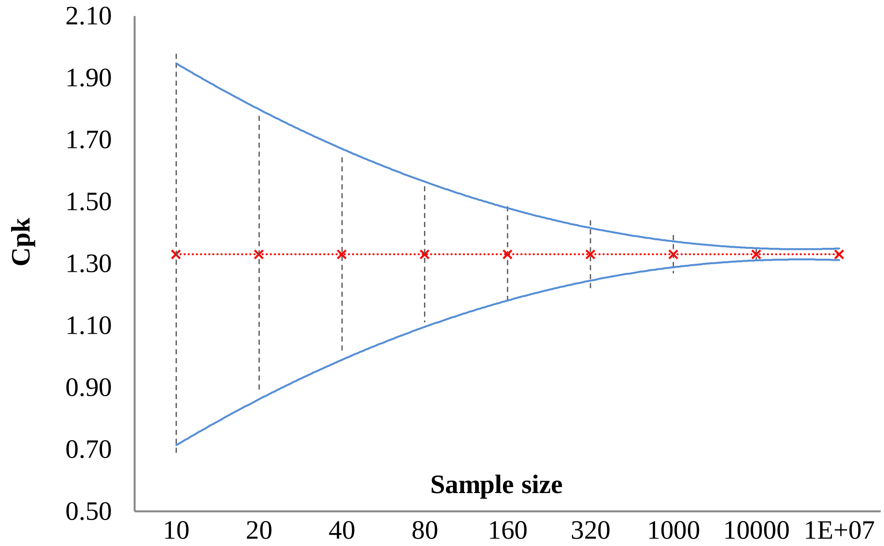
[6] $\hat{C}_{pk}\left(1 - Z_{\propto/2}\sqrt{\frac{1}{9n\hat{C}_{pk}^2} + \frac{1}{2(n-1)}}\right) \leq C_{pk} \leq \hat{C}_{pk}\left(1 + Z_{\propto/2}\sqrt{\frac{1}{9n\hat{C}_{pk}^2} + \frac{1}{2(n-1)}}\right)$ Montgomery, D., C. (2009) *Statistical Quality Control: A modern introduction*, 6th ed. ed, Wiley, Hoboken, 978-0470-23397-9

A PCI in itself has limitations when it comes to carrying information. For example it does not say anything about the costs implied at that particular capability level. However, in combination with cost it can be an effective tool to communicate quality levels and costs. Therefore CoPQ can be a viable concept in understanding machining operations.



	10	20	40	80	160	320	1000	10000	1E+07
Cpk (low)	1.98	1.78	1.64	1.55	1.49	1.44	1.39	1.35	1.33
Cpk (high)	0.68	0.88	1.02	1.11	1.17	1.22	1.27	1.31	1.33
Cpk (target)	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33

Figure 3.6 Size of C_{pk} confidence interval as a function of sample size.

3.2.3 Cost of poor quality and its relation to cost of poor production rate

Two measures of performance of the CNC machining that can be used to indicate process planning effectiveness, are cost of poor quality (CoPQ) and cost of poor production rate (CoPPR), which in part relate to the quality rate and performance rate of OEE. CoPQ can be regarded as a quantitative measure of the associated cost of not having a 100% quality level. In general, CoPQ increases with decreasing process capability. CoPQ can be defined by both internally and externally associated costs. Internal costs relate to costs associated with product quality problems before reaching the customer and often include costs of rework, scrap, repair, re-inspection, down-grading of the final product, extra paperwork etc. (Fering et al., 1998). The external costs include handling rejected parts from the customer, complaint handling (Harrington, 1999), warranty claims, lost sales and loss of good will (Fering et al., 1998) and are often intangible and therefore difficult to estimate. The failure cost can be assessed through the use of different modelling approaches where one solution is presented by Vagnorius and Sorby (2009).

In production, a component undergoes a number of manufacturing process steps, where each process step is followed by an inspection gate. At the inspection, it is judged whether or not the component meets specified tolerances. If not, it can be subject to rework or scrapped if rework is not feasible. A number of such inspection gates, easily results in a complex CoPQ tree model. Production runtime data in aggregated form such as PCIs can be used to calculate the CoPQ for a certain component, which are transformed into probabilities at each specific gate in the model (section 5.2.1). The following definition of runtime data from von Euler-Chelpin (2008) is used: “Runtime data includes all types of data that can be gathered during operation, as well as information synthesised from this data, that are of relevance for evaluating the capability of a real resource”. The probability for each event and the costs for each scenario are multiplied and the sum of all incurred costs is calculated. The CoPQ model and results from a CoPQ study for a machining process are presented in section 5.2.1.

On the other hand, CoPPR can be perceived as the associated costs of not having optimised processes with respect to production rate. It can be exemplified by the selection of cutting tools and machining parameters during process planning. Certain tooling is suitable for a specific machining parameters window and parameters are selected in such a way that the production output rate or the total production cost is optimised. For various reasons, the eventually selected machining parameters are not seldom moderate in relation to what is possible in order to achieve predictable and robust processes. The reduction of machining parameters is not necessarily systematically assessed but is the regular procedure of selecting machining parameters. This is supported by a study performed by Schultheiss et al. (2011) where it was shown that a parametrical study of selection of machining parameters can give machining cost savings. This came as a consequence of optimisation of machining parameters where a systematic methodology was employed to assess the problem.

The gap between the theoretically optimal machining parameters and those finally selected for the machining process can be perceived as the CoPPR. Simplified, this can be illustrated as in Figure 3.7, where different strategies to reduce CoPQ and CoPPR are sketched. The lower left corner in Figure 3.7 depicts the most cost efficient production, since both CoPQ and CoPPR are low, which is indicated by improvement strategy A. Strategy C denotes the above described strategy to decrease CoPQ by lowering machining parameters, which implies a lower material removal rate and consequently lower process rates. These relations are similar to the relation between factors P and Q of OEE.

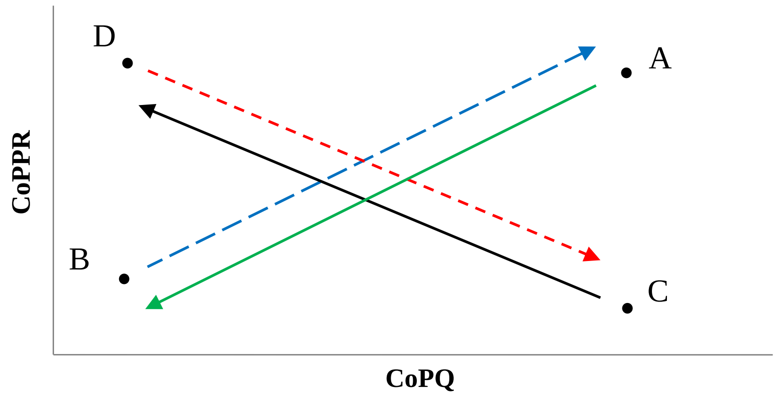


Figure 3.7 Process changes and possible effects on CoPPR and CoPQ.

3.3 Environmentally benign manufacturing

A survey among consumers in the United States revealed that efficient use of natural resources should be one of the top priorities among US manufacturing companies (NN, 2009a). The European Union identified energy consumption as a priority area regarding environmental improvements together with the environmental performance of products and information to consumers (European Commission, 2008). A global survey of the manufacturing industry revealed that economic benefits as a driving force for implementing environmental practices was rated lowest among a number of parameters (Kaebernick and Kara, 2006). Rao and Holt (2005) showed in a questionnaire study among Southeast Asian companies that the greening of the supply chain has a potential positive impact on competiveness and economic performance.

Due to its relation to global warming, carbon dioxide emissions reductions are currently at the top of the global agenda. Since carbon dioxide emissions are directly related to energy production and use, the manufacturing industry, which is a large consumer of electrical energy, should proactively work to meet the growing consumer awareness and achieve potential cost savings by adopting more energy efficient and sustainable production techniques. A historic analogy can be made to mid-19th century England. The Scottish engineer James Nasmyth, famous for developing the steam hammer and machine tools, observed that through technological development and simple measures the power of the steam engines could be multiplied, whereas the coal consumption increased only marginally (Marx, 1894). This rapid development of the steam engine was spurred by the increasing prices of coal. However the result was that both energy and cost were reduced.

In contrast to technological development different governments and the EU have attempted to reduce the energy use through trading permits and taxes. With regulations on the amount of carbon dioxide emissions currently being enforced under the Kyoto protocol, several of the ratifying countries have developed carbon emission trading markets (Kara, 2009). The European Union Greenhouse Gas Emissions Trading System (EU ETS) is one of these that are directed towards certain energy intensive industries in the EU member states. Until the problem with greenhouse gas emissions is solved, it can be expected that more carbon dioxide emission trading markets will be established in the future (Jeswiet, 2008).

One of the main problems is the global nature of the problem and the lack of incentives to limit energy use, since, from a governmental perspective, it is regarded as hampering domestic industry. It is thus essential to identify and highlight the commonality that in many cases exists between cost savings and energy savings. Not only will energy rationalisation lead countries to more easily meet the limitations to greenhouse gases emissions that are imposed, it will potentially also lead to a better competitiveness of the industry in a longer perspective where soaring prices of energy and raw materials can be expected (as is seen in Figure 1.3).

The industrial strategy has often been to improve the environmental performance as a separate agenda, run in parallel or in opposition to the regular cost optimisation schemes. There are however good reasons for considering the environmental aspects of manufacturing and production economics as a whole.

3.3.1 *Green and lean production*

Herrmann et al. (2008) state that green production and lean production have many similarities, where the elimination of waste is the major commonality. Similar observations have been made by Bergmiller (2006) who referred to studies that recognised that lean initiatives can often have positive effects on green manufacturing such as less space needs and less energy need per unit output, coupled with reduced waste. Similar findings were made by Dombrowski et al. (2011), who pointed out the commonalities between lean and sustainable production, as well as conflicting factors. It is not intrinsically so that cost optimised production leads to an optimal solution in an environmental perspective (Herrmann and Thiede, 2008), which means that each specific situation must be evaluated. This is also an area in which further research is needed to better understand the commonality between lean and green production (Herrmann and Thiede, 2008). It should also be noted that the motivation for implementing lean production in the industry mainly lies in the expectations of cost reductions, where the same incitements do not exist for developing more environmentally benign production. Instead, the benefits from a company perspective primarily include increased good will and a marketing advantage.

Minimised process waste and better utilisation rate of the machines, so that standby times are lowered, will work in favour of advancing towards production that is more environmentally benign and lean. However, arguments against the achievement of concurrent lean and environmentally friendly production can also be found, where reduced inventory levels increase the changeover rates, thus increasing the time for non-production (standby time) and e.g. the need for cleaning and disposal of unused process material (King and Lenox, 2001). King and Lenox (2001) found that, due to changes in managerial attitude, there is a positive relation between lean production and lower emissions in production.

The level of quality and its relation to process waste is vital for the overall environmental impact of machining operations. A scrap rate of 10% will lead to an overproduction of the same proportion, with all the environmental impact that the machining operation has. Waste is accordingly negative in both a cost and environmental perspective and is a result of poor process capability and can be caused by inappropriate machine selection for the current product, tooling, machining parameters, clamping etc. All of these factors result in unnecessarily high scrap or rework rates. In this perspective the use of PCIs, such as C_{pk} may be used to indicate environmental performance as well. The influence of capability on machine utilisation and standby times is important. Results of a company case study showed that a substantial part of the machine time was not actual machining (see section 5.2.2).

3.3.2 Energy efficient CNC machining

The main focus in this thesis regarding the development of environmentally benign machining concerns the relation between the energy efficiency of CNC machining and cost efficiency. Focusing on energy as the principal factor can be defended, since energy use is the main environmental impact according to Dahmus and Gutowski (2004). Other environmental impacts of CNC machining include cutting fluids (cleaning, waste management and work environmental issues), noise, lubricants and various other process waste (cutting tools and metal chips etc.). More environmentally friendly production can essentially result from development of technology or methodologies or a combination of the two. Numerous measures exist to improve the energy consumption of a machine tool through better design of the machine tool and its components (Zein et al., 2011). Zein et al. (2011) listed 124 improvement measures for achieving energy savings in CNC machining. Forty percent of these relate to improved machine tool design while 22% of the measures relate to energy reduction through improved process design (Zein et al., 2011). Energy savings gained through technological improvements have a different time perspective than methodological approaches, which can follow instantly after optimisation of routines and parameters. From a lifecycle perspective, Ueda (2004) states that the environmental burden of the machine tool during use accounts for 95%; thus focusing primarily on making improvements in the use phase is sensible.

As been discussed above, environmental concern has traditionally not been considered during process planning. However, with the development of knowledge, strategies and methodologies to address this issue the area can be improved in the future.

Where the total load, i.e. cutting power, increases with increasing cutting velocity, feed and depth of cut, the general tendency is that the specific cutting energy decreases. Specific cutting energy is the energy consumption in relation to the removed material. The specific cutting energy is sometimes regarded as a material property, but this is not fully descriptive, although it is to a large extent dependent on the material properties of the workpiece material. The specific cutting energy is also dependent on other factors, such as the cutting tool geometry and cooling and lubrication methods, as well as on machining parameters (Ståhl, 2008). The specific cutting energy describes the energy per volume unit required to physically form a chip and thus remove the material, and it shows a highly non-linear behaviour in relation to material removal rate (MRR). The non-linearity cannot fully be described by one phenomenon only, and contributing to the complexity of the behaviour is that both the chip and rake sides of the cutting tool are affected (Ståhl, 2008). The magnitude of the specific cutting energy is highly correlated to the chip thickness, which in turn is controlled by the feed rate and, second, by the strain rate that is mostly governed by the cutting velocity (Ståhl, 2008). The specific cutting energy decreases with increasing cutting feed and cutting velocity (see Figure 3.8) up to a certain point where it converges towards a specific value.

Although the physics behind the phenomena is complex, it is easy to experimentally measure specific cutting energy. Data on the specific cutting energy can also be found in handbooks (although often limited in coverage) or calculated analytically. Due to the complex dependency upon material properties, tool/workpiece interface and process parameters, it is also difficult to calculate an accurate value of the specific cutting energy a priori, and experimental measurements must consequently often be conducted.

Either the entire machine tool or the individual components of the machine tool combined must be measured to find values of the total energy consumption. The specific energy required by the machine tool for a certain process is here termed *specific energy*, which should not be confused with the specific *cutting* energy, as was discussed above, which is the energy required to physically separate material from the workpiece. To achieve more environmentally friendly machining, dry and semi-dry machining operations can be used. This leads to a drastic reduction of cutting fluid consumption, since the cutting fluid flow for near dry machining can be as low as a 1/300000 of the amount for flood cooling (Rahman et al., 2002). This influences the total energy consumption of the machining system, since compressor power to distribute and clean cutting fluids is related to the flow rate.

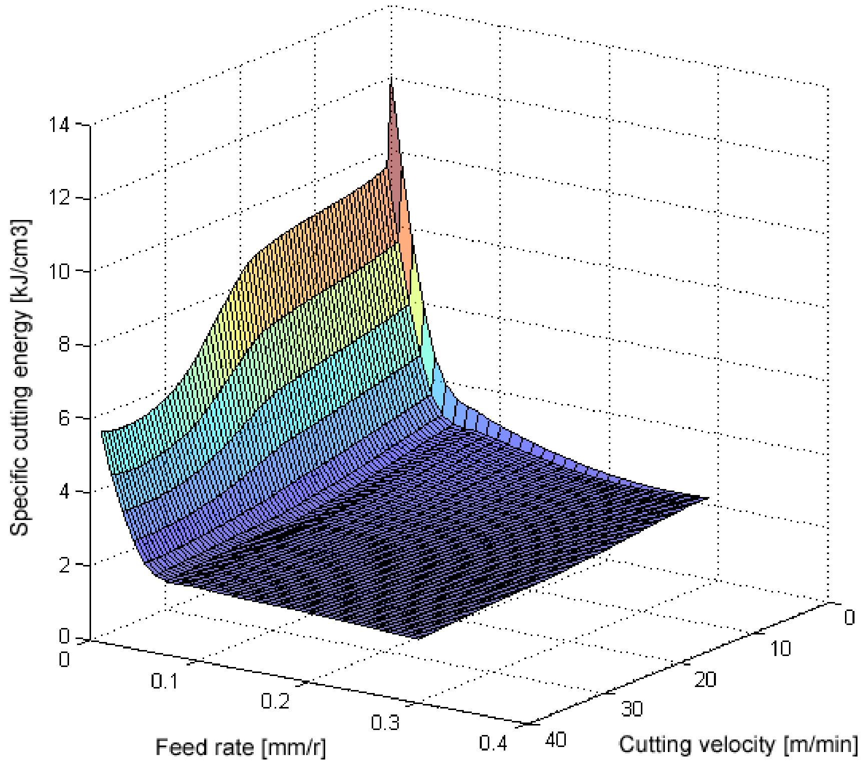


Figure 3.8 Specific cutting energy plotted as a function of feed rate and cutting velocity for the turning of aged Inconel 718. (bicubic interpolation from 25 measuring points).

A few methods for calculating MRR and specific energy are reviewed below. When different machining strategies or processes are compared, it is useful to use MRR as the common denominator and basis for comparison. MRR is also useful since it is linked to production output rate and machining parameters. For a longitudinal turning process, MRR can be expressed as seen in equation 3.6 below.

$$MRR = \pi \cdot D \cdot a_p \cdot f \cdot n \quad (3.6)$$

Where D denotes the diameter (of the workpiece), a_p is the depth of cut, f is the feed rate and n the rotational speed.

During machining, a number of non-value adding operations are typically performed by the machine tool, e.g. initial positioning of the tool, repositioning of the tool and where the material is not cut. An effective MRR can therefore be used to better capture these aspects (see equation 3.7).

$$MRR = \frac{V}{t_m} \quad (3.7)$$

Where V the volume of removed material and t_m denotes the machining time.

The specific energy, u can be calculated with equation 3.8. Where F_C is the cutting force, b the width of cut, t the undeformed chip thickness and η the machine efficiency. However, the specific energy can also describe the energy that must be put into the machine tool in order to remove the material, which is often more relevant from an environmental perspective. Equation 3.9 expresses the specific energy when the machine tool power, P, is used. P is divided by the MRR for the current process. One problem with this value is that only the machining activities are regarded. Non-removing activities (MRR = 0) are not captured and typically P varies during the cut, which makes this measure must suitable to use when different processes are evaluated against each other.

The total energy, E can be used to find the effective specific energy, that most comprehensively describes the whole machining process. E is in the power integrated over time and can practically be calculated as the Riemann sum of a power/time plot as illustrated in Figure 3.9. E in turn is related to the total volume, V of the removed material. This value includes all non-value adding activities necessary to machine the component (e.g. spindle start, repositioning of the tool, entering movements etc.), see equation 3.10.

$$u_1 = \frac{F_C}{b \cdot t} \cdot \frac{1}{\eta} \quad (3.8), \qquad u_2 = \frac{P}{MRR} \quad (3.9), \text{ or} \qquad u_3 = \frac{E}{V} \quad (3.10)$$

Figure 3.10 provides an overview of the different methods to use to calculate the specific energy. Most relevant from an environmental perspective is calculating the total energy use required to machine the intended feature. This means that only studying the cutting process isolated from other factors (i.e. machine, auxiliary systems) will not be sufficient.

Figure 3.9 illustrates a power time diagram indicating the three principal powers. First, fixed power is defined as the power that is not a function of cutting operations. Fixed power is also termed indirect or standby power. The fixed power continues before and after a machining cycle has been executed. It consists of the power from running computers, fans and pumps. Second, operational power is the power demand for operating machine components, i.e. driving axes and spindle rotations when unloaded (Li et al., 2011). Last, cutting power is the power required to physically remove material; if regarded per unit volume of removed material, this corresponds to the specific cutting energy. The two latter, operational power and cutting power, are used in aggregated form in this thesis and are then referred to as direct power, since they are inseparable for the removal of material.

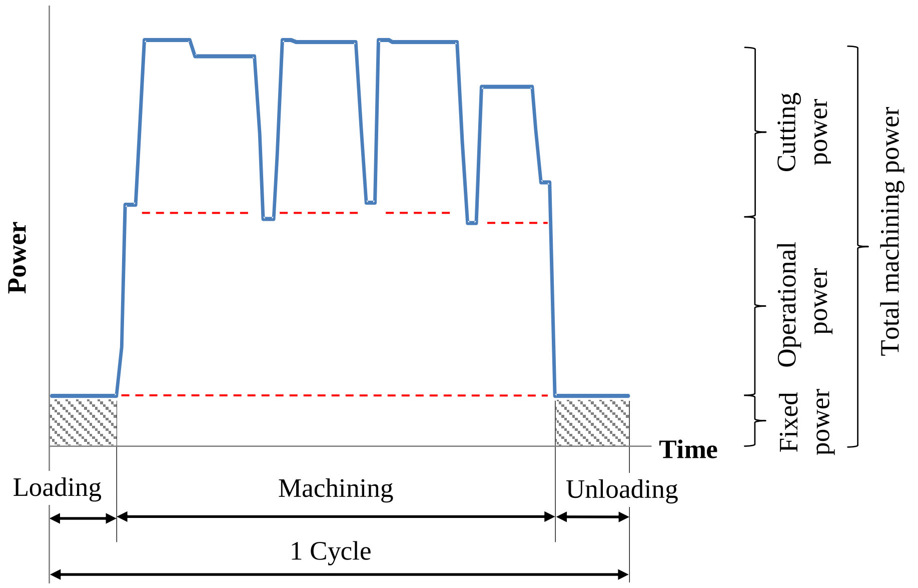


Figure 3.9 Power plotted as a function of time for a CNC lathe with a sample rate of 300 ms.

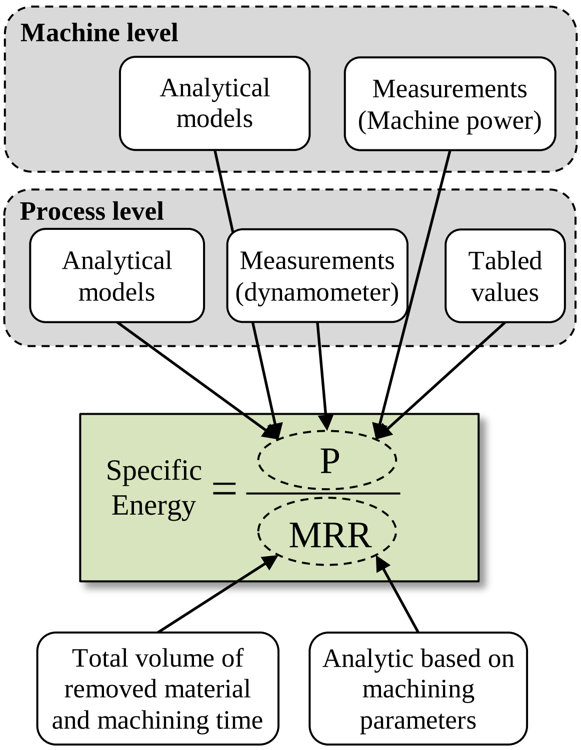


Figure 3.10 Overview of different methods for calculating the specific energy.

Li and Kara (2011) developed an empirical model to describe and predict the specific energy of the machine tool as a function of MRR. A similar empirical model was developed and tested by Diaz et al. (2011) and gave similar results. A model of this kind can be useful for estimating the actual energy use of a machining process during process planning to evaluate different machining strategies a priori. However, since machine tools are complex, with many sub-systems, it is difficult to derive a generic machine tool model. Variations in machine tool capacity, workpiece material and variation of machining parameters lead to difficulties in developing generic analytical models (Kara and Li, 2011). This implies that the principal drawback of using empirically based models is that the models are valid primarily for the criteria tested.

Roughing (and roughing with surface finish demands) and finishing influence the possibilities for achieving energy efficient machining as surface roughness requirements constrain the machining process, since higher MRRs are generally not possible, in particular high feed rates. This means that the full potential of the convergence of the specific cutting energy curve cannot be fully utilised under certain circumstances. However, it is difficult to generalise the possibilities, since it depends on the actual surface finish requirements. In relation to MRR, tool wear must be included, since this is related to machining parameters and consequently MRR. Many types of tool wear exist, but most commonly regarded in tool life testing is flank wear, which typically has a continuous development, although not linear (Shaw, 2005). The flank wear development is characterised by three phases of wear where the first phase is non-linear, the second is linear and the third is non-linear (Trent and Wright, 2000).

One other important aspect of using higher removal rates and higher throughput times as means to increase energy efficiency cost efficiency is that it also influences the economy of scale, in that the machine availability increases due to shorter cycle times. The size of this gain was briefly discussed in Anderberg and Kara (2009).

Researchers and process planners have attempted to reduce the specific cutting energy throughout the history of metal cutting, although not primarily to reduce the environmental impact of machining. Instead, the objective has been to reduce the load and stress on the cutting tool and the workpiece since these are related to tool wear, cutting mechanics, workpiece deflection etc. Rao (2009) highlighted this aspect and discussed various methods for reducing specific cutting energy from a cutting mechanics perspective and where e.g. high-speed machining techniques and chatter reduction methods were highlighted. Narita et al. (2006) presented a detailed algorithm for calculating CO_2 emissions in milling operations and showed that high-speed machining results in a reduction of CO_2 emissions.

Shin (2009) took this approach further by including not only CO_2 emissions but also raw materials, coolant, chips, tool scrap, air pollutants (CO, NO_X, dust, SO_2) etc. These environmental impacts together with the productivity aspects of machining (process speed and machinability) were aggregated into an index that could be used to evaluate different machining strategies. This method was tested experimentally and the results indicated that a higher MRR is beneficial but that a maximum (both high productivity and low environmental impact) is reached for certain feed rates. However, the difference was minor in comparison to the highest feed rates tested. No cost aspects were included in Shin's method, which may explain why optimum was found at very high MRRs. A similar approach was used by Krishnan and Sheng (2000), who developed an environmental index based on energy use and hazardousness (including tool, cutting fluid and chips). When optimising machining parameters for minimum environmental impact, this was achieved at higher MRRs. All the above examples clearly indicate that high MRRs are beneficial from an environmental perspective. However, for some situations, there exists an optimum of machining parameter selection from which a further increase in MRR reduces the environmental performance.

To quantify machining cost, different accounting methods exist. Life cycle costing (LCC) methods are important and incorporate the total cost of an entity's life span. It is a useful tool for comparing different investments because of its high level of detail (Kinnander, 1996). However, LCC does not typically regard energy cost as a variable, which is dependent on different machining strategies and process planning selections, thus providing little understanding for how various costs are related and can be influenced. Enparantza et al. (2006) presented one such LCC for machine tools. On the other hand, traditional machining cost calculation methods do not give information about energy consumption under different machining parameters in relation to other costs. In a CNC machining perspective, it is critical to relate the influence of machining parameters on cost parameters since machining time and tool wear etc. are directly influenced. The same is valid for energy use for different machining strategies. These must accordingly be described satisfactorily in relation to cost parameters to be able to assess the relation between energy and cost for different machining strategies. A suggestion for a model is given in section 5.3.1.

We have now established the fundamentals of process planning for CNC machining by reviewing process planning activities required to generate a process plan and discussed various performance objectives and indicators. The aspect of how much resources may be expended on process planning in relation to production outcome was raised. Furthermore, the influence from changing performance from a process capability and energy efficiency perspective was addressed. The next chapter will go more deeply into the possibilities to improve process planning performance.

4 Aids for improving process planning performance

The chapter has the objective of giving an overview of the possible means to improve process planning performance. A distinction is made between technical aids and methodological aids.

Due to the many different activities involved in process planning, all of which have their respective domain, process planning is the art of combining isolated technical problem solving into a complete concept. To improve the overall process planning performance, various aids targeting specific activities, interfaces between activities, and the system as a whole can be identified. There is accordingly a wide range of approaches for making process planning efficiency improvements. Much research has been done in developing process planning from these various perspectives (Bagge, 2009). The most common approaches comprise automation of specific process planning activities, using expert systems, model-based integration methods and improved working procedures. Besides this, much research has been devoted to developing better algorithms for generating tool paths and optimisation of machining parameters for certain cutting conditions. The latter principally targets process planning effectiveness, while automation in itself chiefly aims to improve the efficiency by reducing the amount of clerical work.

The aim of this chapter is to provide a holistic perspective of efforts already made in the field of process planning aids to increase performance. Figure 4.1 gives an overview of the aids covered.

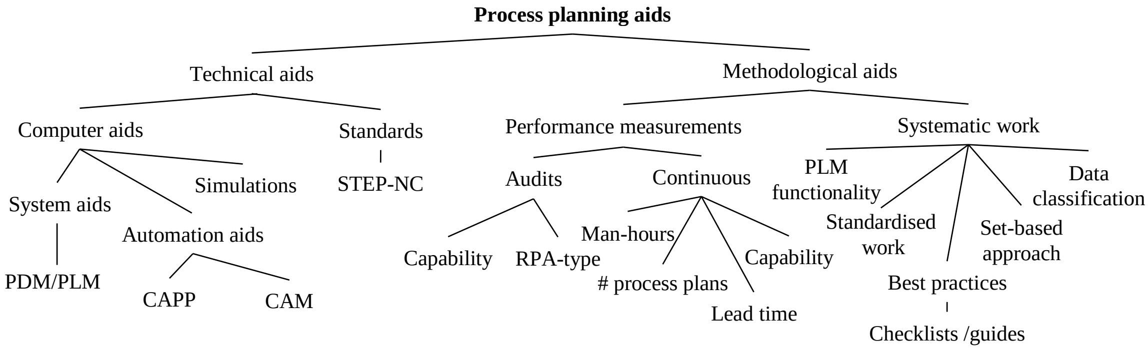


Figure 4.1 Overview of process planning aids.

4.1 Technical process planning aids

4.1.1 Computer-aided process planning

The use of computers to aid or replace persons during process planning is a form of automation, comparable to automation of manual work on the factory floor, but here applied to knowledge work. Automation of manufacturing processes, as well as automation of knowledge work in general, implies a potential loss of flexibility, since the human mind and body is probably the most flexible machine available. The investment cost threshold (in common with most software investments, see section 4.1.5), together with the aforementioned loss of flexibility is one of the main drawbacks of automation in general and for process planning in particular.

Computer-aided process planning (CAPP) is a process planning concept where computers are used to assist or replace humans so that better process plans are produced in less time. The ISO 10303-240 standard (ISO/TC184/SC4, 2005) defines CAPP as "a commercial or proprietary software application used to assist process planners in making a process plan." The CAPP concept stands for a wide span of process planning automation technologies. In its simplest form it will reduce the time and effort needed for process planning and provide more consistent process plans. Although there are multiple choices to be made for machining operations for machining a part, CAPP systems deliver only one process plan (Marri et al., 1998). In their most advanced form, CAPP systems will theoretically produce optimal process plans without human interference from a set of inputs, i.e. the automated interface between design (CAD) and manufacturing (CAM) (Wang and Li, 1991).

CAPP has a long history, starting in the mid-1960s. During the 1970s, initiatives were taken in Sweden in the area of CAPP. Master theses and papers were written in the field and a CAPP system, PRAUTO B2, was developed during this time (Kinnander, 2009). During its history, different areas have been of interest. CAPP is one of the most researched fields of manufacturing (Scallan, 2003) and, up to the mid-1990s, some 300 scientific papers were published in the CAPP field (Marri et al., 1998).

The early attempts to automate process planning work with the aid of computers, primarily consisted of building computer assisted systems for report generation, storage and retrieval of process plans. Chang et al. (1998) claim that these systems can potentially save up to 40% of a process planner's time. Despite a potential significant time reduction, the systems do not perform the actual process planning tasks but merely reduce the amount of clerical work. Later developments of CAPP have been directed towards eliminating the process planner altogether from the entire planning function. Expected benefits and driving forces behind CAPP include:

- Reduced need for skilled planners (Chang et al., 1998);
- Reduced process planning time (Chang et al., 1998);
- Reduced cost of process planning and manufacturing (Chang et al., 1998);

- Rationalisation and standardisation of planning generates more consistent process plans (Groover, 2008);
- Process planners' productivity increase since more systematic work permit more work to be accomplished (Groover, 2008);
- Integration of other applications, such as cost estimation and work standards (Groover, 2008).

There exist a number of variations of CAPP, where a commonly made distinction is made between the variant or the generative method. Briefly described, the variant method builds on the idea that similar parts and features require similar process plans (Xu et al., 2011). This means that features are identified and classified and accordingly given a process plan, based on existing standard plans in a database. For the generative approach a process plan is instead synthesised by regarding part geometry, material and other factors that may influence the machining process (Marri et al., 1998). In this case the process plan is generated through decision logics and process knowledge. The generative approach is a complex method because of its 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). New technologies and approaches to automate and create artificial intelligence of the CAPP systems include the use of feature-based technologies, knowledge-based systems, artificial intelligence, genetic algorithms, neural network, fuzzy set theory/logic, Petri nets, agent-based technologies, internet-enabled, STEP-compliant CAPP, as well as other technologies (Xu et al., 2011).

Despite a long history of CAPP development, the industrial implementations are few. This is particularly the case for SMEs (Denkena et al., 2007). Xu et al. (2011) conclude in a review of CAPP systems that, despite the immense amount of research efforts in the field of CAPP, the effectiveness of these systems has still not reached an adequate level for practical industrial implementation. The authors claim that the principal reasons are that most CAPP systems have a centralised architecture, are vertical in computing sequence and off-line in data processing. This means that adaptive decisions are difficult to make in advance without current machine status (Xu et al., 2011) as well as inefficient computations. Despite the potential strengths of CAPP, there are a number of difficulties that must be overcome to understand why industrial implementation is lagging and will possibly continue to do so if they are not assessed appropriately:

- *Centralisation and outsourcing of knowledge* - When process planning work is automated the knowledge that was previously intangibly possessed by the process planner is transformed into tangible algorithms and decision rules of the computer system. The knowledge is formalised and centralised. This would in the end lead to a situation where the software provider is in possession of the expert knowledge of machining. An interesting issue would be how competition between different manufacturers would materialise if many competing firms use the same CAPP system.

- *Integration aspect* - It is one of the fundamentals of CAPP that the integration with other systems is seamless in order to automate process planning; hence it is essential that a common and standardised file format exists that unambiguously transfers data between different systems. It is vital that geometric dimensioning and tolerancing (GD&T) data is managed, as well as other types of information associated with the products and production. To be able to implement a CAPP system, where the bulk of the process planning activities are automated, an assessment should be made of the interface between adjacent functions. The central issue of this assessment should be to investigate the type of input of information and data to the process planning function and whether these are 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 (Anderberg et al., 2009). It is e.g. not the case that all customers 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, since it is drawn from many different sources. Under these circumstances, it can be difficult to use a CAPP system easily without human interaction (Figure 4.2). The use of standards for managing this problem is presented in section 4.1.3.
- *Novel and innovative machining* - An inherent problem common to all CAPP systems is the difficulties associated with implementing new technology and new machining strategies, since CAPP cannot extrapolate data but only interpolate between existing data, unless this new knowledge is put in the CAPP database. With respect to optimisation of machining parameters, this approach may result in a sensible selection of parameters, but pushing the edge of new and innovative machining strategies is restricted. In contrast, a high performing process planner should to a large extent be able to creatively use available information and data to suggest innovative machining strategies, which are based on experience and/or analytical skills.
- *Performance issues* - Sun (2000) showed a bell shaped relationship between the use of CAPP and performance[7]. Performance was here estimated by the companies themselves and consisted of a number of factors. A limited use of CAPP was regarded more beneficial for performance. There is a flexibility problem where the existing CAPP systems only manage a certain type of features (2D milling, certain turning operations etc.). However, CAPP functionality is today to some extent implemented in many of the commercial CAM systems and then referred to as feature-based CAM (see section 4.1.2).

[7] Notice that *performance* is defined by the authors of the article and is different from the use of the term *performance* throughout this thesis.

- *Implementation lead time* - Sun (2000) underlines the learning time for implementing advanced manufacturing technology (e.g. CAPP), which means that any real benefits are harvested only in a longer time perspective. It is therefore important to provide organisational support and competency development to the users (Sun, 2000) to facilitate effective implementation of the new technology.
- *Industrial adoption* - The industrial adoption of CAPP technology has so far been very limited, where only a smaller number of companies today use some CAPP systems, which also depends on how CAPP is defined in terms of level of automation. There are a number of reasons for this, but clearly there is a lack of maturity in the available commercial CAPP systems, despite intense research efforts in the field over the last 40 years (Xu et al., 2011).

In conclusion, CAPP, despite its many potential benefits, has not reached a satisfactory level of maturity yet for industrial implementation. So, even though humans have many deficiencies, they are still necessary for process planning and, while a completely automatic process planning function is remote, there are methods to automate parts of the process planning work flow.

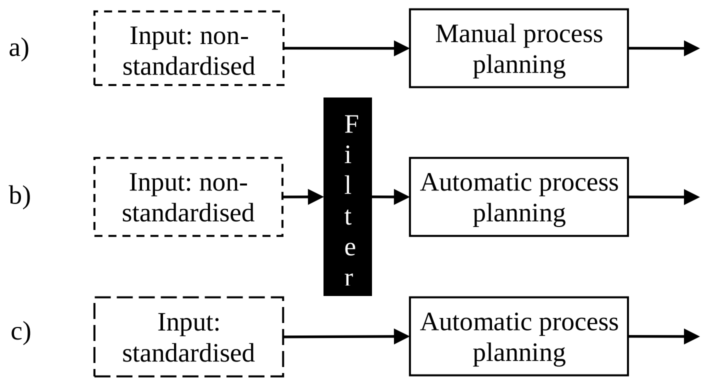


Figure 4.2. Different approaches to overcome problems with input heterogeneity.

4.1.2 *Automation of tool path generation*

The programming of cutting tool trajectories relative to the workpiece is what defines the final part geometry. NC programs are sometimes programmed manually by the process planner from part drawings. The resulting NC program can differ due to the proficiency level of the process planner. This is one of the reasons for automating the tool path generation, which prompted the development of CAM (Wang, 1987). Despite the obvious benefits of CAM, it is still common in the metal working industry to use manual NC programming (see section 5.1). Sometimes it is used for certain products and processes that are performed on specific machine tools, for simple products where it is considered tedious to use CAM or in some cases for all machined products. Use of older equipment, where the control system is not compatible with the current systems and post-processors, may be other areas for manual NC programming.

There are a number of factors behind the automation of tool path generation. Firstly, problems in manually programming complex surfaces spurred the development of methods to automatically use the geometric data of CAD models to create the tool paths for the NC program. Secondly, there are quality problems related to uncertainties in the interpretation of drawings. Thirdly, a reduction of product realisation lead time and cost can be achieved, through automation of labour intensive programming. From the beginning of the NC machine's history, it was realised that NC programming of tool paths would be too tedious to be performed by humans (Chang and Joshi, 2001). Where e.g. 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. The history of CAM began with the development APT (automatic programmed tooling) (Chang and Joshi, 2001) and where APT is a program language that allows the programmer to define machining parameters and tool paths by parameters and geometries. CAM developed from APT, by replacing the program code and enabling programming through a graphical interface (Machover, 1996). In addition to the strictly manual NC programming and CAM programming applications, hybrid concepts exist as well that borrow ideas from CAPP. Feature-based CAM is one example which many of the major CAM providers offer today. This allows the software to automatically detect certain geometric features and assign a pre-defined machining strategy and tool paths, without the active input of the process planner. For manual NC programming systems, there exist parametrised programs for specific geometric features and product families, so that the process planner basically only has to give values to a set of parameters that defines the geometry of a part.

Still today, however, problems exist in the integration between the product design phase and the process planning phase, particularly between subcontractors and their customers. The issue has a long history but there is not yet a generic solution that all companies use. If all the actors in the supply chain that share process planning data do not have a common file format, the data flow chain will inevitably be broken. As will be presented later in the thesis (section 5.1), it is not seldom that CAD data are not used throughout the supply chain. This means that it is virtually impossible to have a seamless integration between the design and the process planning phase. An integrated CAD/CAM system has the potential to transfer GD&T data seamlessly. This is further disseminated in the next section from a STEP-NC perspective.

Figure 4.3 illustrates a possible distinction between different automation levels in process planning. Process planning includes many different areas that can be automated.

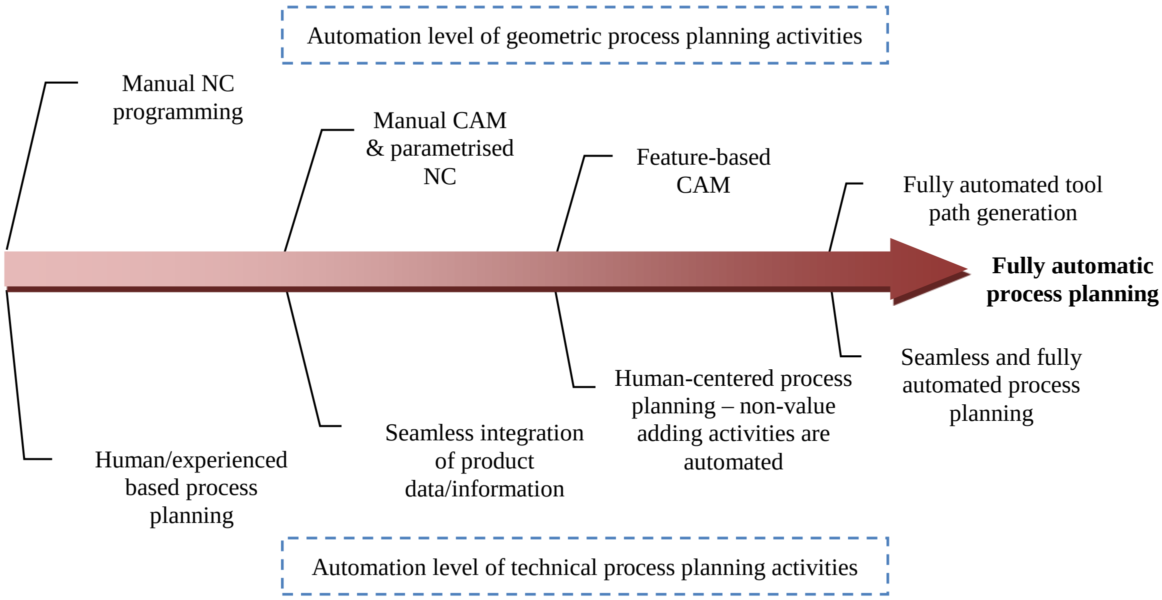


Figure 4.3 Automation level of process planning activities

4.1.3 STEP-NC

With conventional process planning workflow employing CAD/CAM/CNC technology, the digital numerical data chain is broken and information feedback from machining (CNC) is problematic because of only an unidirectional data flow (Rauch et al., 2011). The data flow chain is broken apart by post processing, which translates either drawing coordinates and technical plans or CL-code (CAM) into G-code (ISO 6983). This was the underlying reasons for The STEP-NC standard. STEP-NC (ISO 14649) is a high level language that allows a lossless bidirectional flow of data between CAD/CAM and CNC. A STEP program contains both geometric and technological information, where different parts of the standard specify different machining processes (Zhao et al., 2008). The STEP-NC data format is independent of the type of machine and control system, which implies that postprocessors are not required (Krzic et al., 2009). The bidirectional transfer of information is particularly useful for closed-loop machining, where touch probes are used for on-line inspection, which feeds measured values back to the CNC controller (Zhao et al., 2008).

Rauch et al. (2011) state that, as of 2011, no adaptive STEP-NC has been implemented industrially. At the moment, however, there are no STEP-NC compliant machines and control systems, which means that industrial implementation will take some time (Krzic et al., 2009). Shin et al. (2009) presented a STEP-based CAPP solution where programming is automated (feature recognition, machining strategy, tool path generation and verification), which is under development for commercial implementation.

4.1.4 *Simulation as process verification aids*

Most CAM systems allow simulations of the generated NC program. The simulations carried out in CAM mostly concern verification of tool paths. This means that it is principally the tool trajectories during cutting that are simulated, and the result is that the programmer can verify that the correct geometries are generated with the tools and paths selected. Similar simulations exist for manual NC programming as standalone applications as well as in many CNC control system software. In addition to this type of simulation, there are in general two other possible simulations for verifying that the machining process will deliver.

Firstly, collision simulations of the post-processed CAM program are tested in a virtual environment that must consist of 3D solid models of machine tool, cutting tools, blank, workpiece and fixtures to verify that no collisions occur with the defined tool paths. Collision simulation is an efficient method for 3-axis machining, but is even more useful in 5-axis machining where the axes interpolations are more complex and thus more difficult to predict offline (Lopez De Lacalle et al., 2005). However, collision simulation does not guarantee a machining process free of problems, since these simulations only include geometric information and, in common with offline programming, assumptions must be made about simulation validity.

Secondly, simulations in CAM are static and deterministic, which may not be satisfactory for certain situations; simulations of the machining process dynamics could result in a better understanding of the implications of process planning decisions. For example, being able to simulate chip flow, tool wear and temperatures to test tool and machining parameters without occupying expensive machine capacity may spur innovations in machining strategies or creating more reliable and robust processes already on the desktop. This type of simulation is more complex to perform and sensitive to the quality of the input data (e.g. material properties).

By using virtual tools instead of testing the NC program in a physical setup, much time and cost can be saved, and it can furthermore impose a danger to the operator to machine an erroneous NC program (Xiao et al., 1996). The use of simulations enhances the need of data connected to process planning. Without accurate models of the simulated system, no reliable results can be expected.

4.1.5 *Product Lifecycle Management systems*

Product lifecycle management (PLM) does not have a distinct definition. Grieves (2006) however states that PLM concerns product data, information and knowledge of the entire product life cycle and that PLM is more than simply software. As such, the capabilities of what are usually referred to as PLM systems will be discussed in this section. The aim of PLM[8] systems is to aid the management of products, processes and services from initial concept generation, through design, engineering, manufacturing and to end of life (Ming

[8] PLM is closely linked to the concept of product data management (PDM) and engineering product data management (EPDM), which can be regarded as sub-parts of PLM and mainly comprise the data management aspects.

et al., 2007). Information storage and retrieval, revisions, workflows, roles and tasks can most often all be managed in PLM systems. It can therefore constitute a vital part of the process planning function. CAD models typically only contain parts of the total amount of information that is created and required during the product realisation process. Different functions in the organisation use different information, but some information must be shared. Accordingly, there is a need to collect all information connected to a product so that it is more easily available to all those who need it. Most commercial PLM systems contain 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 do not simultaneously attempt modification of data.

Since PLM systems are cross functional, they must have an interface with all the aids used in order to guarantee efficient information management. With increased use of model-based information and computer software, the demand and drive for standardised representation of information and data increase to improve system integration. This has implications for the whole organisation regarding implementation of e.g. simulation software; that data and information are 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 iterated (Kulon et al., 2006). Pejryd and Andersson (2006) showed that a complete solution of a PLM and enterprise resource planning (ERP) system can virtually manage all types of information required in the organisation.

Implementation of computer aids such as PLM systems provides a fundament for information and data management as well as coordination of work activities within processes. Conversely, the implementation of PLM systems in SMEs has yet not been very successful, which is due to certain characteristics of SMEs as compared to larger enterprises. This is further discussed in chapter 5. The available PLM systems mainly suit in-house mass production manufacturers and many SMEs are sub-contractors to larger enterprises with small batch production and wide product variation (Denkena et al., 2007). Other explanations are limited IT resources and resources dedicated to process improvements (Miller, 2009).

4.1.6 Knowledge-Based Engineering

The traditional approach to 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 et al., 2007). However it is not uncommon in the industry to reuse old process plans and parts of NC programs. Scallan (2003) terms this the workbook approach, where predefined operation sequences are kept in a workbook. A problem arises as soon as the process planning organisation's size and product complexity increases. How can old data be found in the enterprise database? What parts of a previous NC program correspond to a new product? What was the production outcome in terms of the process capability of that NC program? Similar problems and questions spurred the development of knowledge-based engineering (KBE).

In common with many other concepts, KBE lacks a standard definition and consequently many competing definitions exist. 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 focuses solely on the use of knowledge to generate better decisions. The definition resembles the functionality of CAPP, but the two should not be confused. KBE has a more general scope and its level of automation varies, whereas CAPP is strictly limited to the automation of process planning work tasks. Other definitions of KBE focus on the reuse and capture of product and process knowledge (Stokes, 2001), which in turn has a greater resemblance to the PLM concept. However, at the core of KBE is the aim to use knowledge in a more systematic way in order to produce better decisions in engineering processes. Since the aims of KBE are largely covered by the concepts of CAPP and PLM, KBE will further be treated as an integral part of these. As such, CAPP can be seen as corresponding to the more automatic approach of KBE and PLM as corresponding to the knowledge management approach of KBE.

One example of a stand-alone KBE system that aims at bridging the knowledge gap between product design and manufacturing is presented by Molcho et al. (2009). The method (and software) is based on decision rules for knowledge of manufacturability, which can be used during the product design phase. In their system, the data collected were based on interviews with process planners and collected data from sub-contractors.

4.1.7 Automated work instruction generation

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. The instructions are written to guide the operator during machine loading/unloading, tool changes, quality testing, machine monitoring and in-process inspection and control etc. The instructions are often written manually by the process planner, and in most cases, very little standardisation of language and terms is used, meaning that, within a company and between process planners, the work instructions can have different formats and uses of vocabulary for identical work tasks. Using standardised terminology in work instructions not only benefits the machine operators but also enables more efficient information management in databases, where standardised phrases can be reused. The functionality of many PLM systems allows for such semi-automatic approaches of generating work instructions.

The generation of work instructions can also be regarded as a non-value adding activity, since it typically does not contribute to the machining process itself and no optimisations and decisions are made in the writing of instructions; it is merely clerical work. Lundgren et al. (2008) found in an interview survey that process planners dedicate between ½ and ¾ of the total process planning time to the generation of work instructions. This highlights an obvious need for improvements, and the authors proposed a web-based guide to aid the process planner when developing work instructions.

4.1.8 Concluding remarks on technical process planning aids

As seen, different technical process planning aids have different levels of automation and scope with respect to process planning activities. For a better overview, a summary is given according to use in the product realisation chain in Figure 4.4.

When developing the process planning function and effective aids it is valuable to reflect upon the nature of its core - information. Kinsky (1994) defines three information pairs as follows: internal/external information, degradable/non-degradable information, and structured/unstructured information. The different information characteristics impose difficulties in the automatic management and processing of information. When information is used, an evaluation of its reliability is vital for being able to make correct decisions. The capability of the human to critically assess information is one of its strengths. However, to assess information reliability, basic knowledge must exist, and thus a good level of knowledge among process planners is essential if the process planning function is human-based.

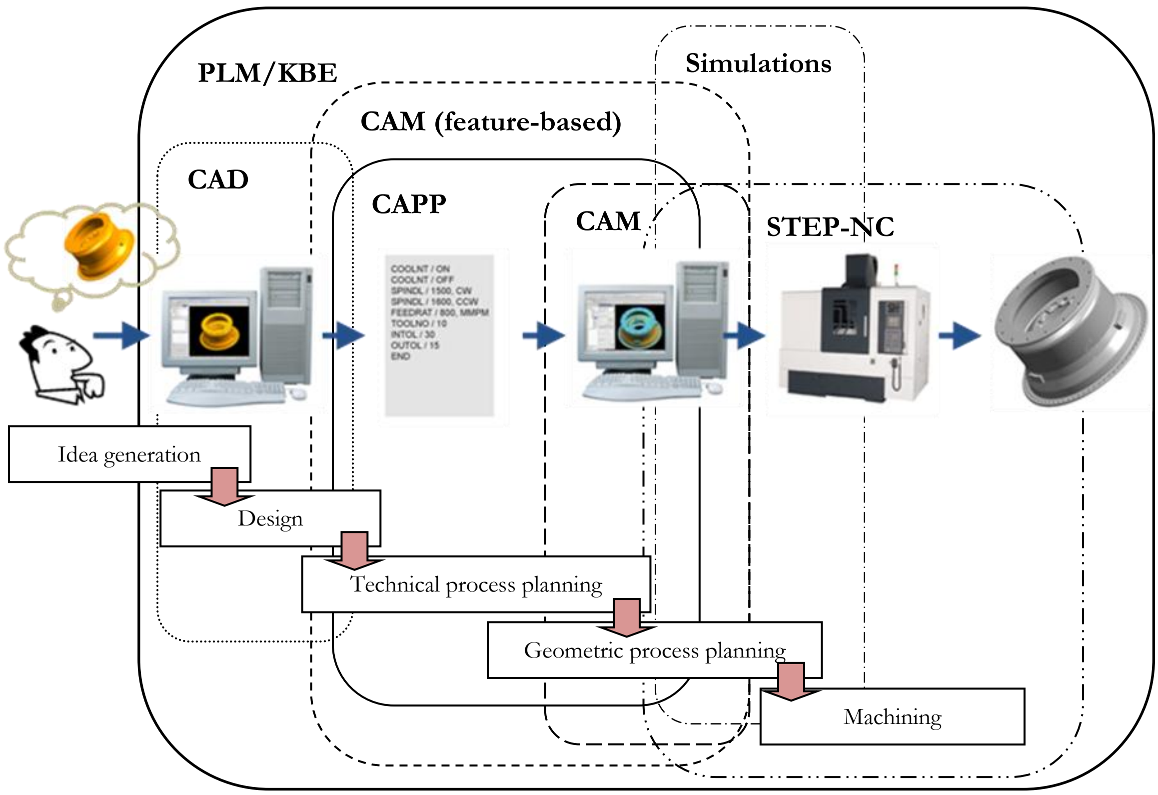


Figure 4.4 Overview of process planning aids and their respective area of applicability.

A possible initial approach to automating engineering work is to free persons from unnecessary repetitive work tasks, such as clerical work and repetitive calculations, so that more time can be dedicated to creative work, where the user is guided through the process (Kulon et al., 2006). The benefit of reusing parts or wholes of formerly defined processes is that those processes have already been tested in a real manufacturing setting. Duplication of mistakes is kept to a minimum, and resources and time spent on duplicating already used process activities can be used for developing the processes, i.e. allowing more time for decision making (Grieves, 2006).

Denkena et al. (2007) identified a number of flaws in knowledge management in particular for SMEs with small batch production:

- CAD/CAM is often implemented in SMEs, while CAPP is not;
- Lack of management of infrastructure knowledge;
- Production process knowledge is not managed, only documented;
- Limited knowledge discovery; hence similar jobs are difficult to identify and consequently a reliance on the memory of employees;
- Digital information is transferred from designer to manufacturer, but there is a lack of digital data feedback from manufacturer to designer.

The above indicates a number of deficiencies in the industry that need to be addressed and overcome. It is also worth noting that the implementation cost of advanced manufacturing technology as technical process planning aids amounts to much more than the purchase price of the systems. Competency development of staff, organisational changes etc. take time and are costly. After a certain time when the technology is fully implemented, integrated and accepted, the benefits of the investment can be achieved. This is often a problematic situation for the organisation, and it is important to enable a faster implementation phase. It is also important to be aware that technical aids are part of the whole organisation, which means that methods and work flows etc. must be adapted accordingly. The methodological aspects of process planning improvements are investigated in the following section.

4.2 Methodological process planning aids

This section discusses the use of methodological aids principally on conceptual level and highlights research presented on improved process planning methods.

4.2.1 Improved work organisation and work flows

The following section will describe a few approaches to improve process planning performance by changes in working methods.

Ward et al. (1995) claim that, in the early 1990s, Toyota was twice as efficient in terms of man-years of development work compared to Chrysler, which was due to a different approach to arriving at product solutions. Later, Toyotas strategy was termed set-based concurrent engineering (SBCE), where final decisions on product design were taken as late as possible in the development process and many different concepts were developed much further than was conventionally was done (Sobek II et al., 1999). According to Ward et al. (1995), the SBCE approach appears tedious and inefficient but the overall performance is better than conventional product development. Sobek II et al. (1999) define three types of product development approaches: sequential, point-based concurrent engineering (CE) and set-based concurrent engineering (SBCE). These concepts can be applied to the activities of the product realisation chain of activities, of which process planning is a part, as well as within the activities.

No examples have been found in the literature where SBCE has been implemented on a process planning level. SBCE is not suitable for regular and recurring process planning work. However, for more complex products and development of machining concepts (to define best practice etc.), the SBCE approach can possibly benefit performance. Contradictory to CAPP, which essentially only delivers one solution (i.e. process plan) to a given machining problem, the purpose of SBCE is to have a variety of potential solutions, where one solution is finally chosen.

The DMAIC (define, measure, analyse, improve and control) methodology originates in the Six Sigma concept and describes a framework to systematically improve processes. Murgau (2009) described such a methodology and its positive results on administrative work (financial control). Despite few similarities between financial control work and process planning, similar methodologies may be adopted. This was demonstrated by Sokovic et al. (2005), who used this kind of approach for process planning work by developing a modified work flow for process planning based on DMAIC and FMEA (failure modes and effects analysis) methodologies. FMEA was employed to correlate key process input parameters (production factors) to key process output parameters (product features), which were then assessed by a Pareto analysis to reduce the number of key input parameters based on their relative importance. Based on this, a modified process planning work flow was designed. The result was that, although process planning cost increased by 40%, scrap costs were substantially reduced so that overall the increased process planning cost was saved in lower production costs, which altogether saved money.

As part of the Modart research project, a framework (produktionslotsen, English: the production pilot) for process planning was developed to guide the process planner through the whole planning work flow (KTH DMMS, 2009). The framework comprises guides for planning of tool selection, clamping, work instructions etc. The aims were to train inexperienced staff to develop their skills in process planning and to work as formal a platform for adjacent work flows (e.g. production investment and plant planning projects).

Hassan et al. (2010) developed a process planning methodology where decisions were supported by the use of Quality Function Deployment (QFD), FMEA and activity based costing (ABC) to aid the process planner in the early phases (macro level) of process planning. The aim was to better assess different production concepts. In the QFD step, the capability of processes was qualitatively evaluated. After that step, FMEA was employed to assess the evaluated concepts' risks and ABC to estimate the costs associated with failures. This approach spurred the development of the conceptual framework presented in section 5.2 that assesses process capability aspects and CoPQ on the micro process planning level.

Bridging the gaps between product development, process planning and manufacturing has been targeted by many researchers. The use of the PLM system (as technical aids) is closely linked to organisation of work. The functionality of many PLM systems allows the manager to assign tasks, work flows etc. to specific persons and roles. Using all functionality incorporated in the systems implies decisions about the organisation; hence this part cannot be overseen.

Many attempts to design efficient and effective process planning aids have treated the process capability as a discrete entity, with a focus on developing algorithms to produce process plans for certain geometries, e.g. Li and Liang (2010), as part of a CAPP system. Newman and Nassehi (2009) presented another approach to adapt process plans according to the actual status and capability of the current manufacturing resources, where e.g. machine status and current tool wear could be included. In reality, machining processes are stochastic; hence variations emerge on different levels of the machining process, both in the short and the long term time perspectives. This adds another dimension to be included in the resource profile of the planned process. It is vital to manage these variations effectively so that the products and production process are robust for real manufacturing conditions. Newman and Nassehi (2009) treated the capability of processes as discrete entities.

Whiteside et al. (2009) proposed a concept to increase the manufacturability by utilising process capability knowledge in a progressive development model during product design. This approach to improving manufacturability through design can prove to be viable (similar to DFA/DFM), where estimates of the process capability can already be achieved in the design phase. However, as mentioned previously, it is often difficult to estimate process capability, especially if processes are not known to manufacturing engineers and process planners involved in estimating process capability. There is thus a need to better understand the underlying manufacturing processes and what the capability indices actually indicate in terms of process capability.

4.2.2 *Performance measurements*

Although performance measurements are not an explicit prescription for how to carry out work or even how to redesign workflows, they are essential for developing an organisation. As the old devise reads, "one cannot improve what one cannot measure"; individual processes must be measured in order to be managed effectively. Therefore a brief section on performance measurement is included here.

The essence of a performance measurement system is to provide accurate information (Tangen, 2007) so that effective decisions and actions are enabled (Kennerley and Neely, 2002). Busby and Williamson (2000) state that ".. systematic measurement of organisational outcomes, giving feedback with the results and using them to set precise goals (all) increase performance." The quote suggests that one of the central aspects of performance measures is the feedback of the measures back to the process, since it is not the performance as such that is interesting from the internal company perspective, but how the measured processes can be improved (Bond, 1999). A set of performance measures and metrics is valid for a certain point in time.

When discussing performance measurements, it is also essential to define the fundamental parts of the measurement system. A performance indicator can be perceived to consist of two parts – a measure and a metric, where the indicator itself relates to a certain attribute. A differentiation can be made between a *measure* and a *metric* according to the IEEE standard glossary, where a measure is a standard, unit or result of a measurement (NN, 1983) and a metric is a quantification of the degree to which a system, entity or process possesses a given attribute (NN, 1990).

Performance measurements must also be performed with reasonable effort (Hannula, 2002), so that capturing measurement data is not cumbersome, time consuming and costly. Collection of performance data is preferably automatic. It is thus also important to define how to carry out measurements (Jonsson and Lesshammar, 1999). Using already employed performance indicators can be effective so that product and production measurements that have already been made can be used. Most organisations have some performance indicators, but the scope differs, and data collection varies as well, where some companies measure every product and process extensively, whereas others only measure a smaller sample of the products and the production process not at all. Almström and Murgau (2008) noted that it is not uncommon that companies have too much data, as a consequence of automatic computer logging.

A major difference between performance indicators for production activities (e.g. assembly work or CNC machining) and non-production activities (e.g. administrative work or engineering work – such as process planning) is that the outcome of the latter activities is not defined products or services. One of the reasons for this is that engineering work tends to be performed by organisations where the contribution from specific activities is often unclear in relation to specific outcomes (Busby and Williamson, 2000). Other features of non-production work are the tendency towards an unclear distinction between different activities in the process: the process flows consist of information rather than of material (Murgau, 2009). Altogether, the above characteristics of non-production activities make them difficult to measure.

When designing a performance measurement system it is important to regard the aspect of environmental variables, which are factors that have an influence on the design outcome, but cannot be influenced by the personnel (Busby and Williamson, 2000). This is essential, since if e.g. production runtime data are used to indicate process planning effectiveness, the impacts of operators, machines and the manufacturing system at large must be singled out, since these factors are not controllable by process planning only.

Principally two approaches to assess process planning performance can be identified: continuous measurements versus audits. The former represents the day-to-day measurements collected throughout the organisation (on the shop floor as well as in the office). Process planning performance indicators here include man-hours, lead times, finalised process plans for process planning and lead times, quality, scrap, capability, utilisation, downtime etc. in production. Conversely, the audit approach is only performed during a limited period of time and most commonly by one or several experts in the audit process. Examples of the audit approach, although not targeting process planning, are Goodson's (2002) *Rapid plant assessment method* and Almström and Kinnander's (2011) *Productivity potential assessment method.*

In the empirical research presented in this thesis, the use of performance measurements in a number of companies was investigated from the perspective of their maturity level for implementing performance measurements of process planning. The survey and analysis method were based on literature, where five principal pillars of a mature organisation for performance measurements were defined. These pillars and their respective base in the literature are described hereunder.

- *Understanding company goals and customer demands in relation to process planning* - Process knowledge, and an understanding of company goals in relation to the process input and output, are vital for the establishment of performance indicators. It is thus important for companies to be able to relate the intellectual work, such as process planning to company goals and the business idea (Roos and Roos, 1997).
- *Scope of the present measurement systems* - Tangen (2007) states that it takes time and requires experience to design an effective performance measurement system – it is therefore relevant to take into consideration the scope of the present measurement system when studying the readiness for extending its scope. A more elaborate performance measurement system also increases the likelihood that performance indicators can be used to measure the performance of process planning as well. As mentioned above, certain performance indicators, e.g. the manufacturing process, can be analysed in a different context and then give a partial indication of the process planning performance as well.

- *Automation level of the present performance measurement system* - The implementation of performance measures must be relevant and it must be cost efficient for the companies to run the measures. Therefore the usage of automatically collected data is ideal.
- *Definition level of process planning* - One of the most fundamental aspects of performance measurements is that the process that is to be measured must initially be identified, at which e.g. inputs and outputs of processes are stated and the input of resources is given (NN, 1995).
- *Process planning improvement focus* - The companies' future competitiveness and development are the main purposes of performance measurements. Performance measures should be defined so that they support improvements (Neely et al., 1997) and are part of a conscious improvement strategy in the company.

4.3 Interdependence between the technical and methodological aids

A schematic illustration can be constructed to summarise the content of chapter 4 (Figure 4.5). To enable high performance through the implementation of advanced process planning technology, a number of prerequisites must be fulfilled or measures taken. It should be noted that it is only the potential performance that is pictured and the order between some of the aids can potentially be altered. Performance here mainly concerns process planning efficiency, since technological process planning aids in themselves do not provide more advanced solutions for metal cutting problems per se.

In total, much more research efforts have been expended in developing technology to aid process planning than on the methodological and managerial side of process planning. This thesis has contributed in compiling carried out research in both of these fields and highlighted the need for a synthesised approach to improve process planning. This is further explored in the next part of the thesis. There is also a gap between state of the art from a research point of view and the industrial situation, as we will see when we advance into the next part of the thesis.

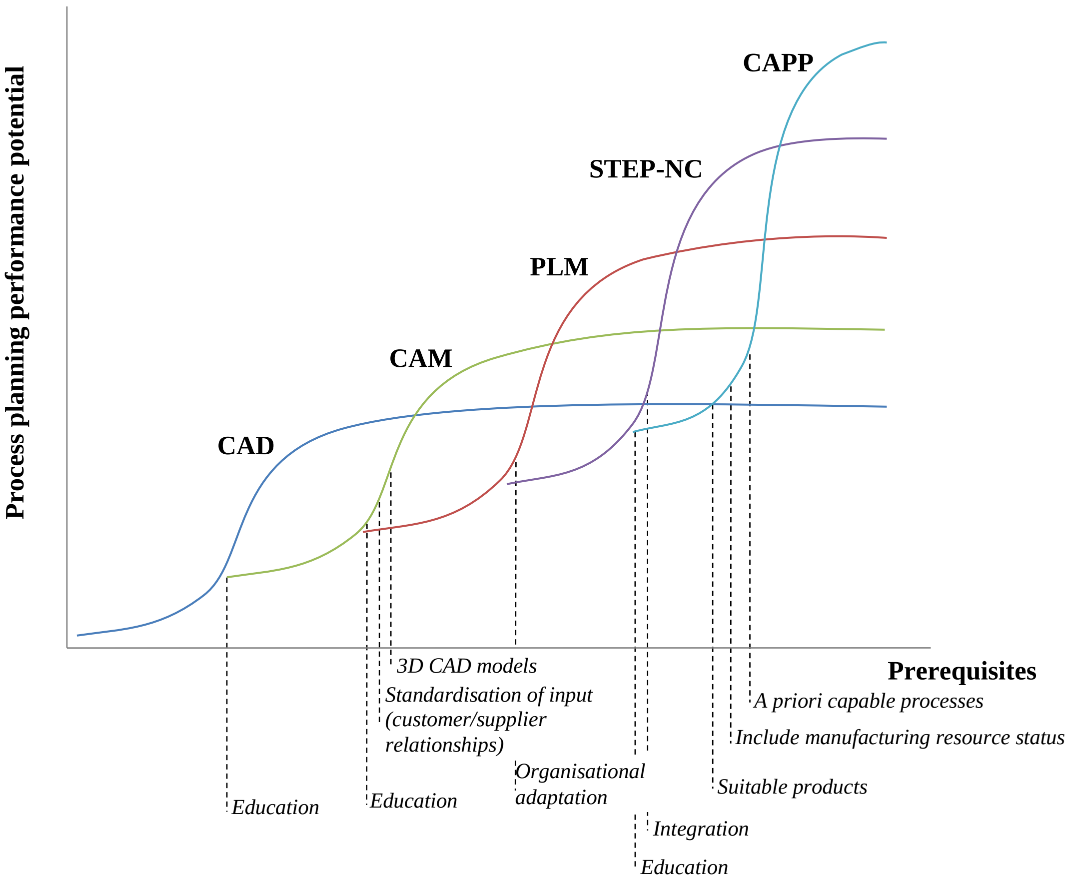


Figure 4.5 Potential effects and prerequisites for different process planning computer aids.

Part III

Research

5 Empirical results

This chapter is structured according to the research performed. First results from surveys are presented and discussed, which principally concern process planning efficiency and the industrial use of process planning aids. The work and results on process planning effectiveness in terms of process capability and energy efficiency are presented in two different sections.

The aim of the research presented in this thesis has had a wide scope, where many aspects of process planning have been studied. Figure 5.1 illustrates the areas of contribution of this thesis. Four surveys were conducted which primarily aimed at achieving a better understanding of process planning in the industry. The results extracted from these surveys present some problems that the industry faces and indicate the current use of process planning aids and use of performance indicators. These studies mainly focused on the efficiency of process planning and do not regard process planning effectiveness. The results of these studies are presented in section 5.1. Process planning effectiveness was in turn investigated from a process capability perspective of CNC machining. Employing PCIs as operation selection criteria was proposed and problematised by analysing the effects that different measurement methods have on the possibilities to design intrinsically capable machining processes. These findings are presented and discussed in section 5.2. Process planning effectiveness was furthermore studied from the perspective of energy efficiency of CNC machining. It was investigated how different process planning decisions influence energy use and is presented in section 5.3.

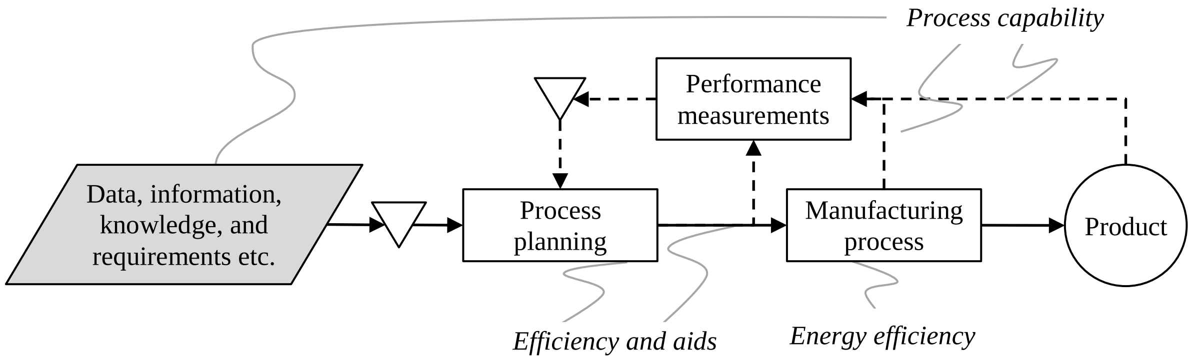


Figure 5.1 Overview of results in relation to aspects of process planning.

5.1 Results from surveys of process planning

The aim of these surveys is to first describe the state of the industry[9] in relation to the research presented. Based on these findings, the aim is to better understand how aids can be developed to support the industry to advance its current positions.

Subsequent sections present the findings from the four surveys, but first a brief summary of the primary findings and consecutive order of surveys are given. A lack of efficient process planning was indicated in a survey of metal working companies, which could be traced to difficulties in information management during process planning and unclear indicators of process planning efficiency. A second survey was conducted to understand the act of process planning in the industry and the level of automation of process planning activities in greater depth. A third survey was designed to focus on the industry's level of maturity for implementing process planning performance measurements, which was indicated as a deficiency in the first survey. By the end of the project, a fourth survey was designed to capture any change in the use of process planning aids from the time of the first survey, and whether environmental impact is considered during planning. Table 5.1 presents for each of the surveys the aim, scope and method etc. The following sections will present the findings. Not every question in the surveys will be reviewed here, but the complete responses of all surveys can be found in Appendix A to Appendix D.

Table 5.1 Overview of the four surveys.

	Survey 1	Survey 2	Survey 3	Survey 4
Aim	Process planning efficiency, computer aids, company prerequisites	Use of computer aids, process planning work flow, information input types	Use of performance measurements and indicators for process planning	Use of process planning aids, problematic areas
Scope	Metal working industry	Metal working industry (subcontractors)	Metal working industry	Metal working industry (subcontractors)
Research method	Mailed questionnaires	Interviews (on-site)	E-mailed questionnaires	Web-based questionnaires
Sample size (# respondents)	42	6	12	144
Response rate	40%	100%	23%	25%
Methodological purpose	Exploratory, descriptive	Exploratory, descriptive	Descriptive	Descriptive

[9] Industry here exclusively refers to the Swedish metal working industry, except for survey 2 where noted.

5.1.1 Survey 1: Process planning methodology and efficiency in the Swedish metal working industry

The investigation was based on a general hypothesis that more systematic process planning implies higher process planning efficiency, which is a defendable hypothesis with respect to the reviewed process planning aids (Chapter 4). This was described as a causality model from which the questionnaire was designed. Since all organisations (here, process planning organisation) act in a specific context, organisational prerequisites were included as well. These factors were incorporated in three indices used in the analysis (Figure 5.2).

The response rate in the survey was 40%, which implies responses from 42 companies from all over Sweden. Companies that were approached were found in the Scandinavian automotive supplier association's roll, the subcontractor website "industritorget.se" and companies known to the researchers. The questionnaire was aimed at persons in the companies with a holistic view of process planning in the respective company. The companies were consequently approached in a phone call to find a suitable person and establish a relation prior to sending the questionnaire. It was necessary to use a mail-based questionnaire in order to be able to include a larger number of companies in the study. The respondents' answers were returned anonymously. The survey was conducted during the spring of 2008 and consisted of 57 questions distributed over four parts. The questionnaire comprised open ended, nominal and ordinal questions. Survey response is first presented as descriptive statistics, and then hypotheses are tested, additional analyses are provided and conclusions are given.

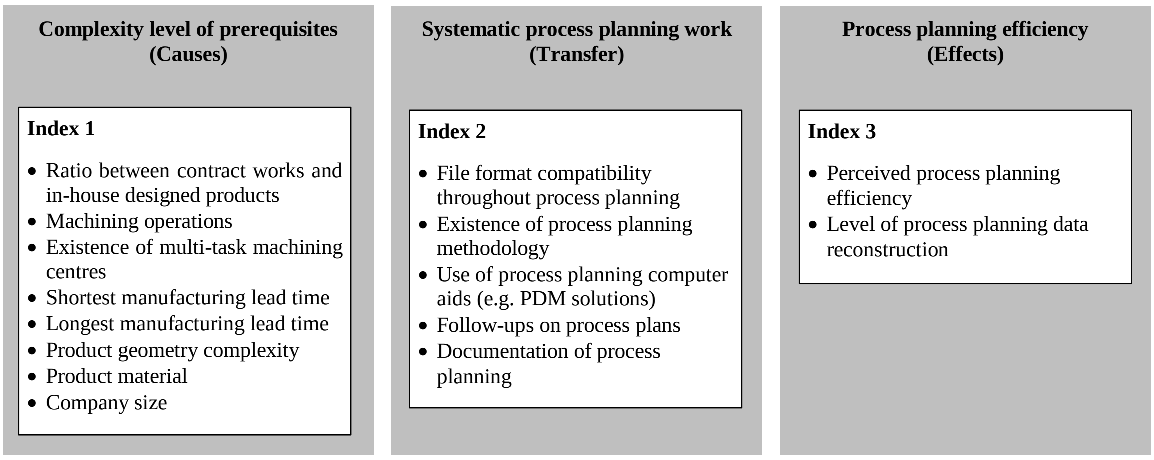


Figure 5.2 Description of the three constructed indices.

Characteristics of responding companies

The following section presents the characteristics of the responding companies, where specific data referred to are found in Table 5.2.

The nominal process planning time is less than eight man-hours for 50% of the companies. This indicates a limited complexity level of the products for a majority of the companies and/or products belong to product families where new process plans largely consist of reused information, similar to the workbook approach. The rest of the companies have a rather large variation in process planning time, where 12% of the companies use more than 80 man-hours for planning a process. The highest was 500 man-hours.

The responding companies are primarily subcontractors without their own design responsibilities (74%), but a fifth of the companies have mainly in-house design. For the major part of the companies (74%), metal cutting stands for more than 50% of the manufacturing.

Table 5.2 Compilation of companies' response.

Process planning time (man-hours)

Less than 4h	4-8h	8-40h	40-80h	80-160h	160-	Blank
24%	26%	14%	7%	7%	5%	17%

Proportion in-house design

0-25%	26-50%	51-75%	76-100%
74%	2%	2%	21%

Proportion metal cutting

0-25%	26-50%	51-75%	76-100%
17%	10%	24%	50%

Shortest manufacturing lead time (raw material -> deliverable product)

Less than a week	More than a week	Blank
57%	40%	2%

Longest manufacturing lead time (raw material -> deliverable product)

Less than a month	More than a month	Blank
33%	60%	7%

Proportion of process planning time dedicated to acquiring new information

0-25%	26-50%	51-75%	76-100%
50%	43%	7%	0%

Proportion of process planning time dedicated to recreating information

0-25%	26-50%	51-75%	76-100%
48%	45%	7%	0%

Proportion of former process planning work that can be reused

0-25%	26-50%	51-75%	76-100%
29%	29%	31%	12%

Regarding time distribution during process planning, 50% of the companies spend between 0-25% of the time on acquiring (searching for and retrieving) new information. New information refers to information that is new to the process planning organisation and thus has not been used previously. This includes finding information on tools, machining parameters, materials etc. It should be noted that 7% of the companies use more than 50% of the process planning time to acquire new information. 52% of the companies spend more than 26% of the process planning time on recreating information, i.e. information already or previously used by the organisation but not readily available for reuse by the process planner when needed for the current task. As seen, the companies state that a substantial proportion of earlier process planning work can be reused in planning for new processes. More than 70% of the companies state that at least 26% of process planning work previously performed can be reused. For the characteristics of each of the respondents (title, level of education and experience) in the companies, see Table 8.1.

Use of computer aids

As was discussed in chapter 4, many different types of computer aids are available, where Figure 4.5 indicates some prerequisites for achieving better performance in relation to a particular computer aid. The state of the industry in terms of having acquired some of these prerequisites is presented below.

Figure 5.3 illustrates the use of 3D CAD models in the companies and thus gives an understanding of the use of digital data communication and the possibilities for using model-based data for process planning. In terms of 3D CAD model use a division can be observed between the companies that use very little or no 3D CAD models, i.e. 43% companies have less than 25% of their planned products as 3D CAD models. On the other end are companies where the bulk of the products are available as 3D CAD models. This group consists of 33% of the companies, where the proportion of products available as 3D CAD models is greater than 76%. Looking at the next category in the column chart (Figure 5.3), it is seen that the companies in which any substantial part of the process planning is carried out in 3D are in the minority; thus 26% of the companies have more than 50% of their process planning in 3D. Manual NC programming is still carried out in 86% of the companies (Table 5.3), which means that the implementation of CAM in Swedish industry is not complete. 22% of the respondents have more than 50% of their non-products (tools and machines) as 3D CAD models. This figure is rather high since most CAM applications work without specific models of tools and machines, and accurate models of machine etc. are needed mainly for collision simulations.

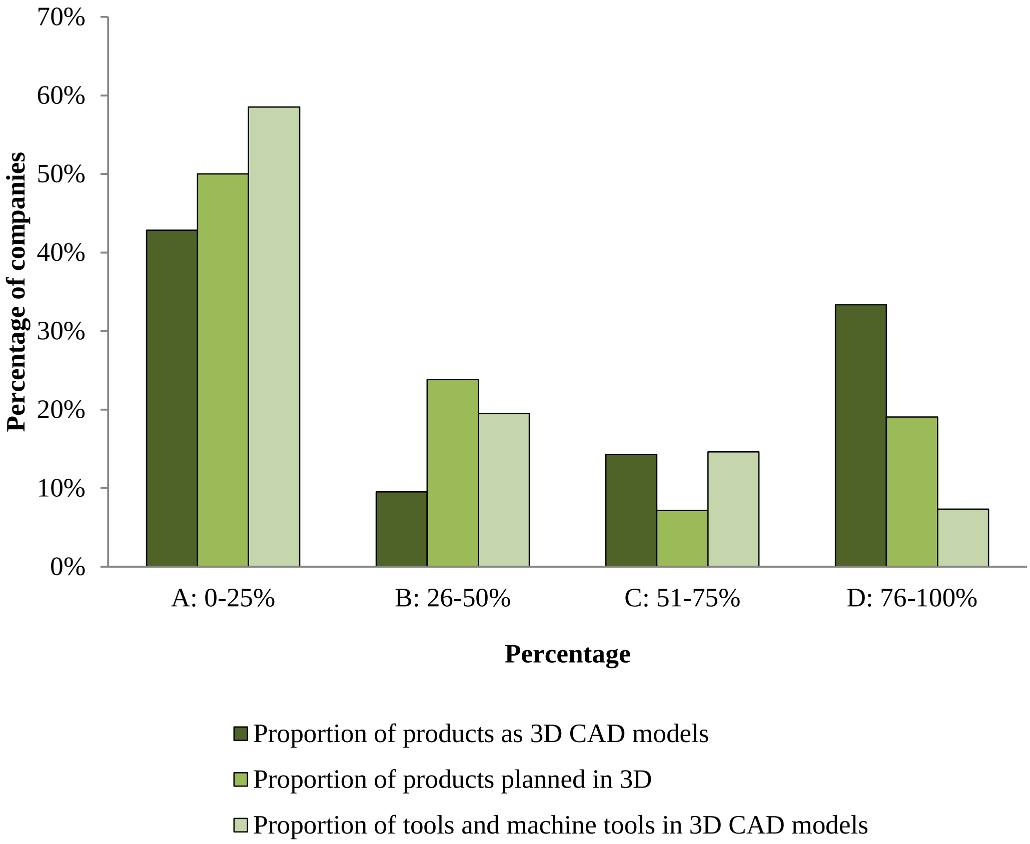


Figure 5.3 Histogram of the use of 3D in the companies, where A, B, C and D correspond to the extent to which responding companies use the stated technology.

Table 5.3 contains some other features regarding the use of and the possibilities to effectively use computer aids for process planning. A slight majority of the respondents claims to have no file format compatibility throughout the product realisation process. Furthermore, roughly half of the companies state compatibility to be a key factor when selecting a CAM system. The use of PDM/PLM systems and similar computer aids for process coordination to support process planning was found to be small in the surveyed companies, where only 19% of the companies had such support in place.

To enable "the digital factory" and a highly integrated and model-based product realisation process, seamless integration of data is vital. A hindrance here is the industrial reality, where legal matters can potentially block technological advancements. This is illustrated by this survey, where half (Table 5.3) of the companies do not consider CAD models to be legally binding for producing an order, which means that additional documentation and paper drawings must be provided. Another influencing factor may be the immaterial property aspect, where 3D CAD models can be considered as providing the supplier with sensitive information (which was expressed by one company in survey 2).

Table 5.3 Prerequisites for compatibility of surveyed companies.

	yes	no	blank
File format compatibility throughout the product realisation process	46%	54%	-
Compatibility aspects stated as important when selecting CAM system	44%	56%	-
Use of process coordination computer aids e.g. PDM/PLM systems	19%	81%	-
Proportion of companies using manual CNC programming	86%	12%	2%
CAD models legally binding to accept orders	45%	50%	5%

Hypotheses testing

As described above, a hypothesis testing was developed by constructing three indices. The first index was the level of complexity of prerequisites, describing the process planning difficulty for the company. The second index was the level of systematic process planning work and was defined as the level of structured process planning work and the existence of an explicit or tacit process planning methodology. Process planning efficiency was the third index, based on one factor describing the companies more subjectively and one that describes the efficiency more objectively (Figure 5.2). Possible correlations between the indices were analysed by means of linear regression. Table 5.4 presents the hypotheses and respective Pearson correlation (r), which indicates that no correlations appear to exist between any of these indices. This means that there appear to be no correlation between systematic process planning and process planning efficiency. It is similar for prerequisites' influence on the existence of systematic process planning, implying that company size, product complexity and production lead time do not have an unambiguous relationship to the level of systematic process planning work. Last, a more difficult process planning situation does not appear to correlate to lower process planning efficiency.

Table 5.4 Tested hypotheses and correlation.

Hypothesis	**Tested indices**	**Pearson correlation, r**
A: Companies with more systematic process planning, more often experience a higher efficiency than companies with less systematic process planning.	Index 2 => Index 3	0.206
B: Companies with higher complexity level of prerequisites, more often have more systematic process planning than companies with lower complexity level of prerequisites.	Index 1 => Index 2	0.283
C: Companies with higher complexity level of prerequisites, more often experience lower process planning efficiency than companies with lower complexity level of prerequisites	Index 1 => negative Index 3	-0.041

Two tailed significance test

Further analysis
Since process planning efficiency as studied here is a compound of efficiency perceived by the companies and the information reconstruction level, it is valuable to study the relation between the two. The perceived process planning efficiency was however not found to be correlated to the process planning information reconstruction level (Figure 5.4). The information reconstruction level may be considered a more objective indicator of efficiency, although it is still based on respondents' estimations, since it is not quantified through measurements. Despite being only a partial indicator of process planning efficiency, information reconstruction has a significant effect on the whole process planning function, since 50% of the companies estimate that they spend 26% or more of process planning time on reconstructing information. Figure 5.4 indicates that 33% of the companies may overrate their efficiency, since 14 companies claim to have good or excellent process planning efficiency and at the same time state a data reconstruction level of 26% or more. This figure in itself gives a hint of substantial efficiency improvement potentials in the responding companies. This indicates an improvement potential between 15 and 40% with an average of 27%, calculated from the companies' own figures[10]. It is then apparent that information management is a significant issue in many of the companies and that methods and aids to improve the situation are needed. Otherwise the consequences are that a majority of the companies investigated will use a substantial part of their resources without adding direct value to the product[11]. This implies longer process planning lead times and higher product cost.

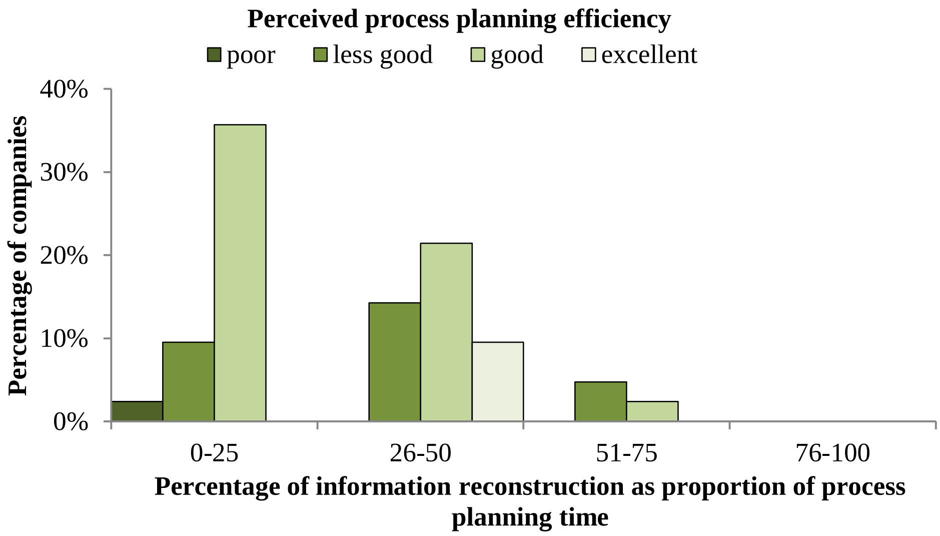


Figure 5.4 Histogram of perceived process planning efficiency vs. data reconstruction.

[10] The question was formulated so that the companies selects an interval (0-25%, 26-50%, 51-75% and 76-100%) of the level of data and information that must be reconstructed, i.e. data that the process planner previously created for a specific process and can be reused for new process plans, but the process planner must spend a substantial amount of resources on finding the specific information.

[11] This is value adding from a process planning perspective, which refers to work activities resulting in a producible process plan.

There is however a strong tendency for the larger companies in the survey (with more than 100 employees) to be more critical of their own process planning efficiency than smaller companies (fewer than 100 employees) (Figure 5.5). The underlying explanation for this tendency was not investigated in the survey, but possible explanations may be a better understanding of performance in larger companies, organisational problems with a large number of employees or deficient methods for managing the process planning organisation. However, these presumptions cannot be validated with such a small sample as this survey is based upon; hence further work is needed.

It is interesting to note that, among the three companies with more than 250 employees, none have any computer aids (e.g. PLM system) to coordinate process planning. It can only be speculated, whether this explains why these companies claim problems in process planning efficiency. The proportion of smaller companies (18%, fewer than 100 employees) among the responding companies that use any computer aid to coordinate process planning is roughly the same as for the companies with more than 100 employees (22%).

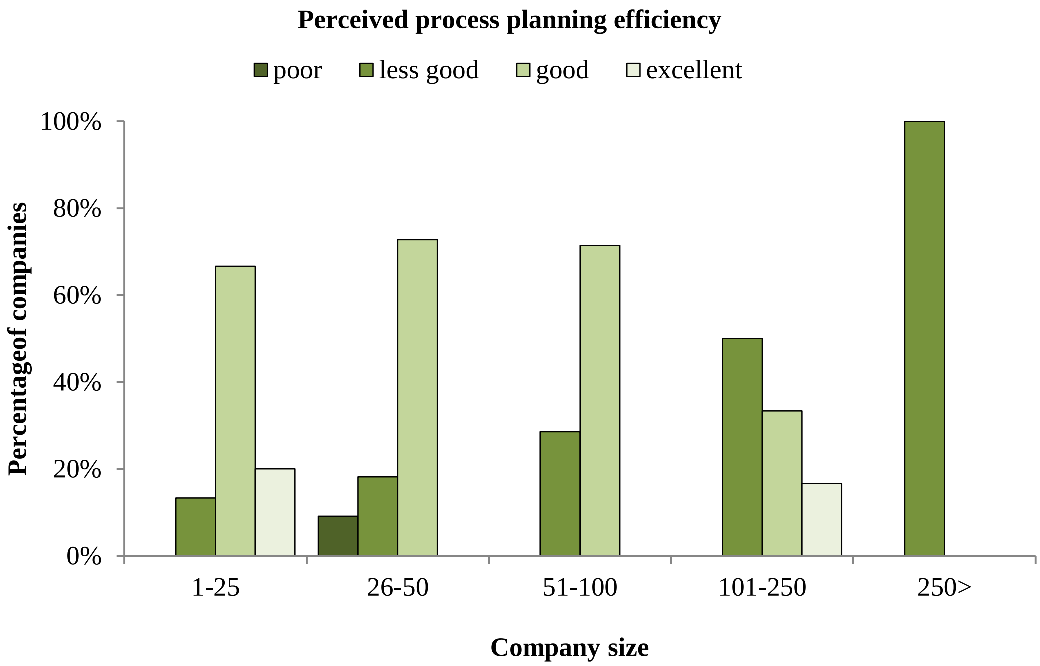


Figure 5.5 Histogram of perceived process planning efficiency vs. company size (i.e. number of employees).

On the basis of the above results, it appears as though the responding companies have little knowledge about their own process planning work and actual efficiency. This stance is further supported when considering that none of the responding companies refers its perception of process planning efficiency to any performance indicators or measurements. When asked to rate the company's process planning performance, a motivation for the answer was also requested. Some companies here mentioned their communicational and organisational platform, while others referred to personnel characteristics. Nevertheless, it is a unsatisfying finding that so many of the investigated companies have little knowledge of their process planning performance, since it significantly influences the possibilities for making effective improvements, if no performance indicators are available to monitor changes made.

5.1.2 Survey 2: Automation level of process planning work

The survey focused on the automation level of process. Six metal working companies, that had a primary focus on CNC machining of different sizes, types of products and production were interviewed on-site. The study was conducted between December 2008 and May 2009. Between one and six persons were interviewed in each company, and a process planning workflow for a nominal product was sketched for each company. The workflows contained the principal activities and the various aids and data/information repositories, and were constructed using standardised building blocks (Figure 8.1). This method was used to visualise, to more effectively communicate and avoid misunderstandings and to gain an understanding of the complexity of the workflow. One such workflow is seen in Figure 5.6. Characteristics for each company are found in Table 5.5.

Interviews and workflows were afterwards analysed and the level of automation at each company was defined from a five-dimensional level of automation scale. This model incorporates the primary work activities of process planning. The criteria for each level are given in Figure 5.7 as a polar diagram and Table 8.2. The five dimensions defined were generation of tool paths, tool selection, machining parameters selection, fixture selection, and NC program verification, which are all vital process planning activities and where commercial computer aids are available.

Table 5.5 Characteristics of the surveyed companies.

Company	Business area	Supply chain position	No. of employees at plant	Process planning role	Production volume	Machining of 3D features	Location	# inter-viewees
A	Aerospace	OEM/ODM/subsupplier	~2300	Process planner	Medium/large	Yes	Sweden	4
B	Hydraulic equipment	ODM/supplier	~300	Process planner	Large	No	Sweden	4
C	Heavy automotive	OEM/subsupplier	~150	Process planner	Large	No	Sweden	2
D	General engineering	Subsupplier	~10	Process planner/operator	Small/medium	No	Australia	1
E	Heavy industry	OEM/subsupplier	~80	Operator/ Process planner	Small/medium	No	Australia	1
F	Tools, mold & dies	Sub-subsupplier	~20	Operator	Small	Yes	Australia	1

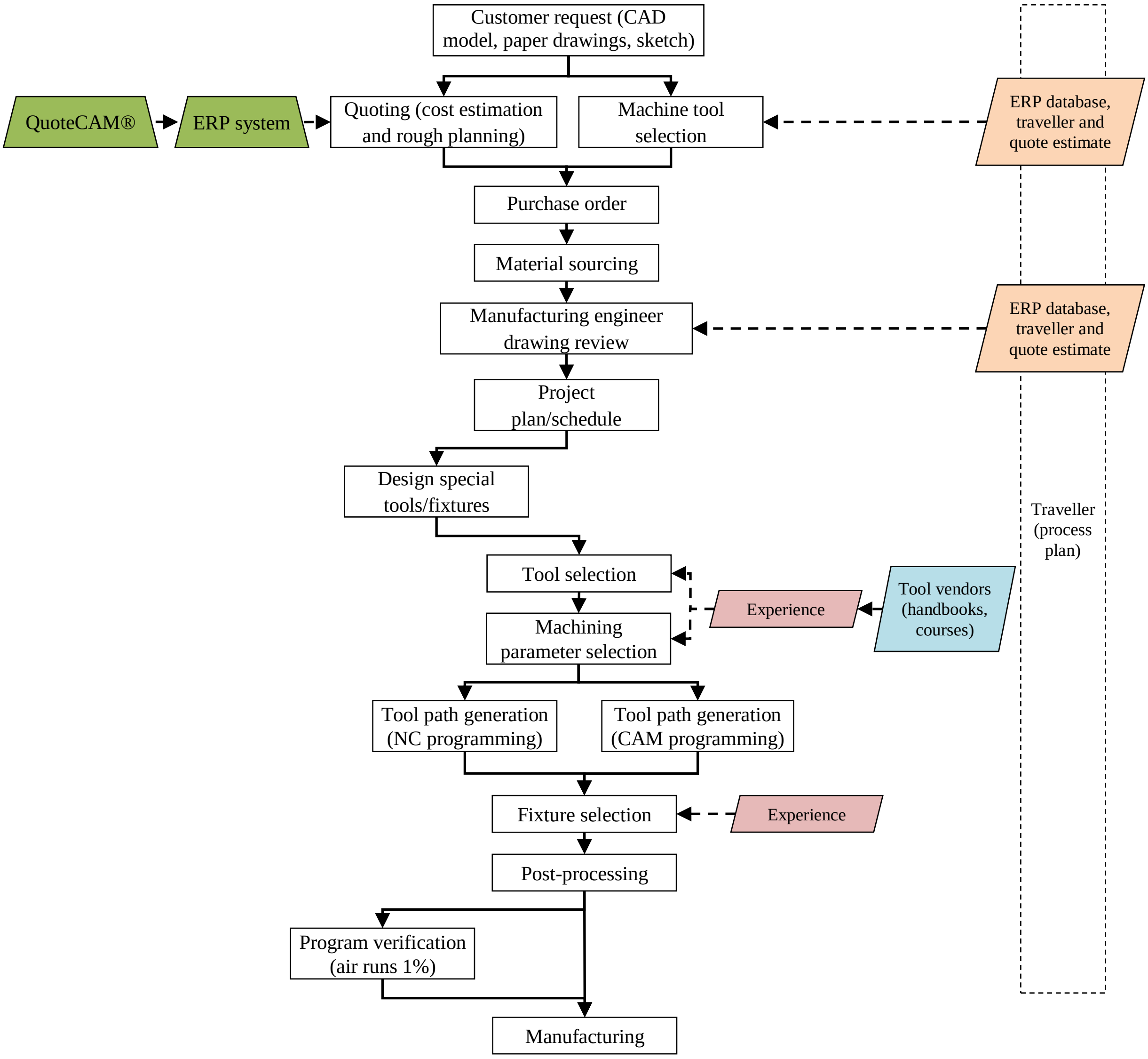


Figure 5.6 Flow chart of process planning work at company E.

The survey showed that, for some companies, in particular sub-contractors with a high share of non-regular customers, interface issues are one of the problems in automating the process planning function. Their customers provide product data and requirements in shifting formats and standards, such as CAD models, sketches sent by the fax, printed drawings and extensive product specifications. This was one of the explanations given by some of the companies for not using CAM. If CAM is the only planning method used, then all products must be transformed into CAD models, which is time and resource consuming. However, one company (B) only had in-house design and CAD-based product data, but still used manual NC programming. The explanation in this case was that the company previously (some 20 years ago) had attempted to implement CAM, but experienced problems in the machining of the post-processed CAM programs. The company currently did all NC programming manually. The company's product belonged to large product families with altered dimensions. Company C used a similar approach, where NC program parts were reused extensively, thus resembling the workbook approach, although without consciously defined sub-programs.

Company A stands out in comparison in terms of program verification. Most of the companies had no verification simulated in the machine controller or in CAM. Due to the high cost of errors in production, company A carried out numerous CAM simulations and collision simulations of the post-processed NC program as well.

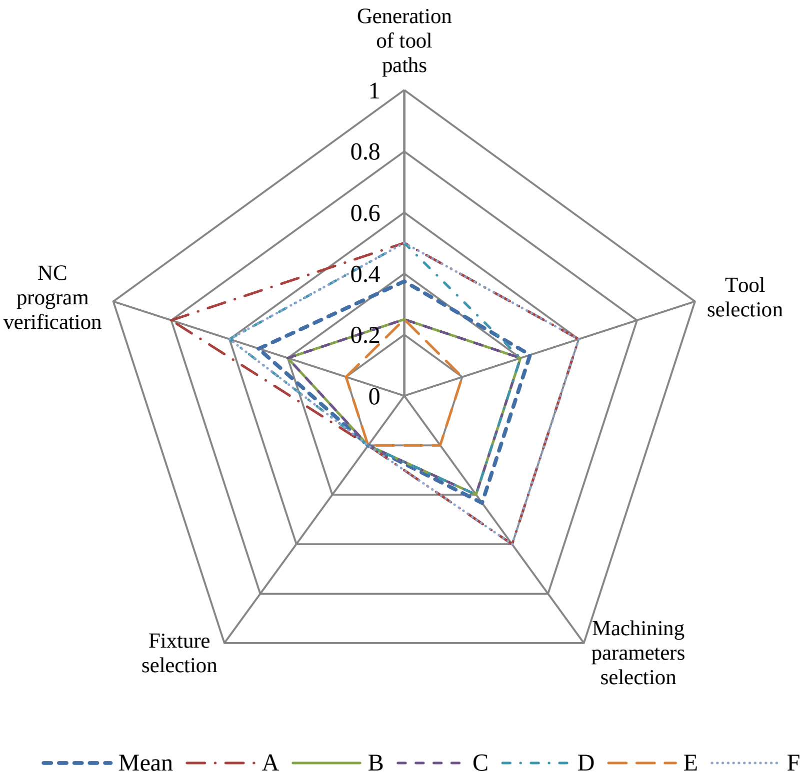


Figure 5.7 Process planning automation level of surveyed companies.

Furthermore, the survey indicated that there is generally little concurrency between process planning activities in the surveyed companies. This is mainly because of the relatively small size of the companies, where some of the studied companies only have one or a few process planners and where each planner is assigned a specific part. Some companies also referred to reorganisations over the years, where the work procedures changed from a functional division of labour at times towards product focused division of labour.

In order to make any general statements about not only the companies in this study, but the metal working industry at large, it is necessary to study a larger sample of companies. Despite the small sample, the study has provided valuable insight into different companies' state of process planning. It is also worth mentioning that the companies do not generally have a systematic approach to managing revisions of process plans. A process plan implemented in production is seldom revised once it has proven to work, i.e. to produce a part within specifications.

The general impression among the companies was that the resources were not available for continuous improvements with respect to revising process plans in order to improve machining performance. This reasoning is not applicable in some companies in the study, since the production volume was limited to only a few parts and process plan revisions would not contribute to overall performance.

Despite there being three Swedish and three Australian companies, no significant differences in approach or communicated problems were perceived. The situation appeared to be similar, although no general conclusion with respect to the global nature of process planning can be drawn from only six interviews.

The main findings of the survey provide an enhanced understanding of the prerequisites for making advancements in process planning, where the main results are:

- Low level of standardisation of input in some of the companies;
- Low automation level of process planning - few computer aids were used for process planning;
- Data, information and knowledge are generally not managed systematically, although the companies seemed aware and had some informal systems, based on spreadsheets, ERP or PLM.

5.1.3 *Survey 3: Industrial maturity for process planning performance measurements*

As a sequel to survey 1, a survey was designed that directly addressed performance measurements. The questionnaire was distributed to 53 Swedish metal working companies during April 2009, which generated a response rate of 23%. The questionnaires were e-mailed and were to be filled out and returned by the respondents. The survey was not anonymous, since the information was not regarded as being of a sensitive nature. The companies approached were primarily the ones that responded to the first survey. The survey was based on a five-pillar model developed to define the readiness level of the industry for implementing performance indicators of process planning. The questionnaire consisted of 16 questions sent by e-mail. The model was based on literature and was revised as described in section 4.2.2 concerning performance measurements in general and non-production processes and the use of performance indicators in manufacturing specifically. Table 8.3 (Appendix C) contains the complete questionnaire with questions and response.

The overall findings of the survey are presented in aggregated form in a polar diagram (Figure 5.8). The five measurement pillars are individually plotted against an aggregate of each category's individual average. The aggregate form means that no individual company can be singled out; all results presented here are the average of all companies.

The strengths and weaknesses of the investigated companies are illustrated in the chart. The chart was constructed by using the sum of all positive answers under each area and dividing them by the sample space, thus creating a non-weighted index describing the companies' fulfilment of each pillar identified. The axes (0-1) should be interpreted as the possibility to meet the defined criteria in each of the five pillars. A result lower than 0.5 means that less than half of the criteria are met, while an average of more than 0.5 means that more than half of the criteria are met. The findings under each pillar are presented below.

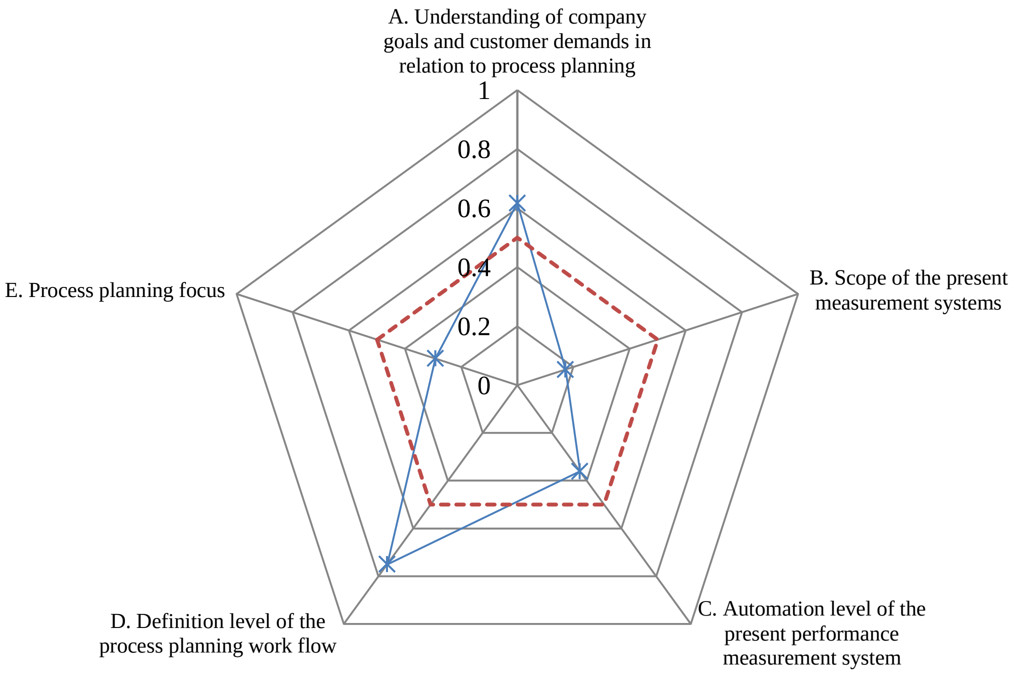


Figure 5.8 The blue (solid) line represents the average for the investigated companies, while the red (dashed) line illustrates the mean at 0.5, where half of the criteria are met.

A. Understanding of company goals and customer demands in relation to process planning

In the companies that responded there is a slight positive lean towards company goals and objectives being understood and reflected upon in the organisation. 75% of the companies state that process planners have an excellent understanding of their work in relation to company goals. It should also be noted that 33% claim that performance indicators are not related to any company objectives, which implies that some companies measure for the sake of measuring, without any apparent reason. (five questions targeted this topic in the survey)

B. Scope of the present measurement systems

The scope of the present measurement system covers both the general measurement system and the potential measurement system for process planning. Allowing the companies to state which performance indicators they use gives an understanding of the present measurement system. The survey shows rather limited process measurements, thus indicating that the quantitative knowledge about production is limited to the indicators used. Of the exemplified performance indicators, i.e. six financial and eight non-financial measures the companies measured only 28% and 24%, respectively, of these. As seen in Figure 5.8, the scope of the present measurement system is in one of the weaker areas in the investigated companies.

It is interesting to note that 42% of the companies measure the total manufacturing lead time, but only one company regards this as an indicator of the performance of process planning. The process planner probably has the greatest influence on machining lead time, once the definite product design is decided upon and the production system is given. It is somewhat contradictory that 50% states that manufacturing cost can be used as a performance indicator in process planning, since manufacturing lead time is a vital part of cost. Scrap rate is the most commonly measured (50%) and this is regarded by 42% as an indicator of process planning performance as well (four questions targeted this topic in the survey).

C. Automation level of the present performance measurement system

The survey revealed that 50% of the companies automatically retrieve manufacturing performance data but only 25% use that information. The automated collection of performance data is not well supported in the responding companies (three questions targeted this topic in the survey).

D. Definition level of process planning

Responding companies appear to be aware of their process planning, since they claim it to be well defined regarding roles and activities. Interviews in survey 2 indicated that although the companies have flow charts describing the processes, the level of detail was not revealed and there were more filed documents than living documents, thus not always up to date (one question targeted this topic in the survey).

E. Process planning improvement focus

Improvement focus and strategies are important, and the principal use of performance measurements should be to support improvements through quantified performance data. The companies' focus on improvements of process planning was addressed by two open-ended questions in the questionnaire allowing the companies to state their focus on increased quality and productivity. These answers were interpreted in terms of whether any serious focus was present. The proportion of missing responses was large in this question, which was interpreted as a lack of an outspoken improvement focus; hence the overall score of this issue was low (two questions targeted this topic in the survey).

The conclusion drawn in survey 3 is that the level of maturity is on average low among the companies that responded in terms of implementing performance indicators and measurements of process planning. Overall, the companies have a rather limited scope in the present measurement system; data collection is instead manual (human resources are required to collect data) and the focus on process planning as the key function for achieving performance objectives is not explicitly stated. However, there appears to be a fair understanding of performance objectives of the company in relation to process planning. Before implementing performance measurements, the individual company should assess shortcomings that have been identified and in particular use performance indicators that are related to performance objectives, since there is always a risk of having too much data and not being able to use them appropriately.

5.1.4 Survey 4: Use of technical and methodological process planning aids

The questionnaire survey was developed to request a minimum of the respondents' resources to fill out; hence a total sample size was prioritised over survey scope and in-depth questions. In total the questionnaire contained 18 questions plus additional comments. The following areas were included in the questionnaire:

- Use of digital information and computer aids;
- Use of performance measurements and standards;
- Use of environmental performance indicators;
- Deficiencies in process planning;
- Company characteristics.

The survey was distributed to 600 companies that had formerly responded to earlier surveys and companies found at the sub-contractor portal "industritorget.se". In total, 144 companies answered, which gave a response rate of 25%. The questionnaire was web-based, and each company's websites were visited to ensure that their main business was CNC machining and, if possible, contact details for suitable persons in each company were retrieved. The survey was conducted in December 2011.

Digitalisation of process planning work

A total of 33% of the companies do not use 3D CAD models whatsoever, and half (50%) use it less than 10%. On the other side of the scale, there are companies that almost exclusively use 3D CAD models (Figure 5.9a). 11% of the companies have more than 90% of their parts as 3D CAD models. On average, 30% of the industries' parts exist as 3D CAD models, although the median is only 10%, which shows the great variation in the population. The findings were similar in survey 1.

The use of CAM resembles that in the CAD situation (Figure 5.9b). The average here is 35% and the median 12%, which can be explained by the fact that 2D and 2.5D

CAM systems exist that do not require 3D models. Altogether, the two situations are similar, but the use of CAM shows an even more parabola appearance than the use of 3D CAD models where 32% of the companies do not use CAM at all, whereas on the other end, there are companies which prepare the bulk of products in CAM.

Having additional data (tools, machining parameters, requirements specifications etc.) stored digitally simplifies and facilitates advancements towards computer-aided process planning. As seen in Figure 5.9c, it is common to have some digital data, but 22% of the companies still have no digital data whatsoever. On the other end 14% of the companies have their data exclusively in digital format. It should be noted that digital data in this case do not imply that the data are stored in a database or can be seamlessly integrated in process planning work.

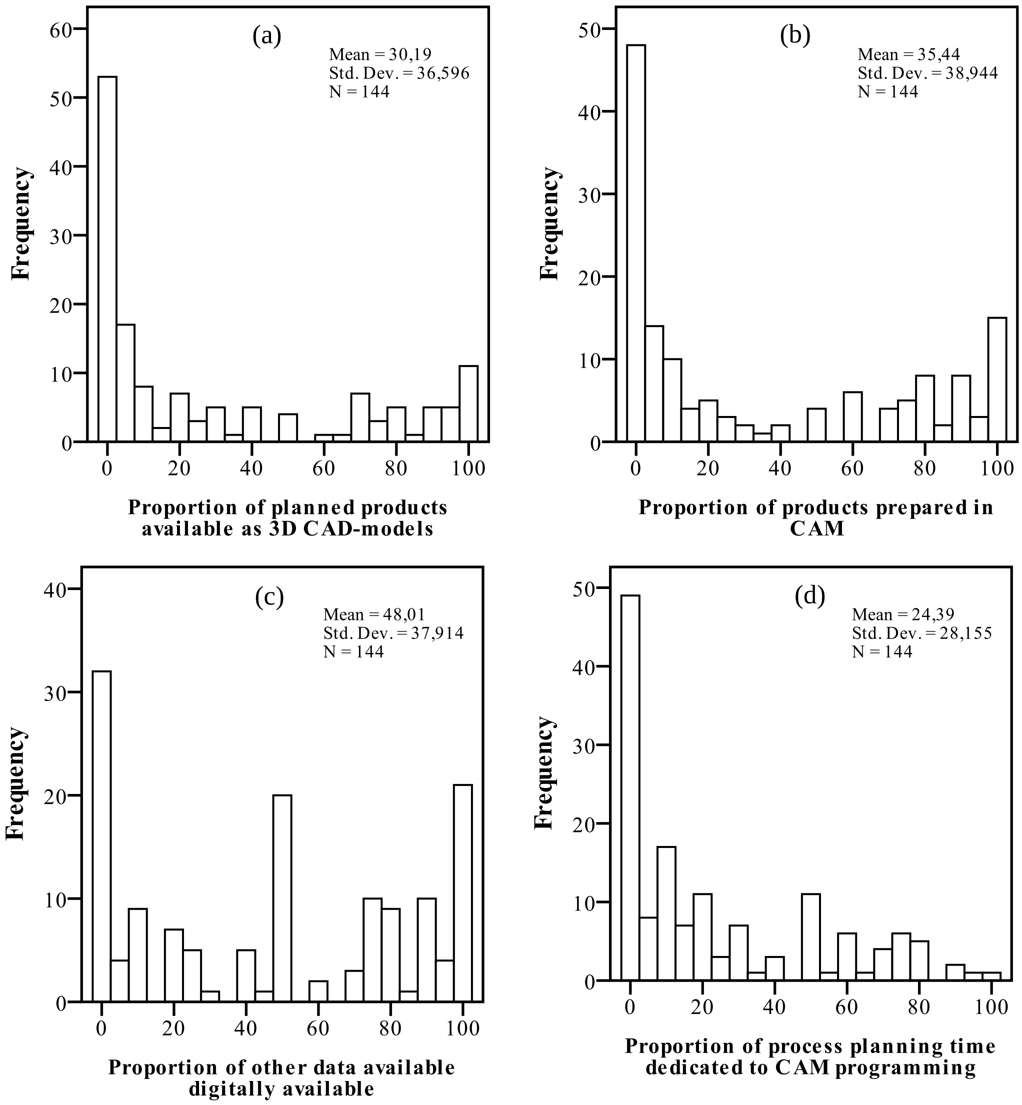


Figure 5.9 (a) Use of 3D CAD models. (b) Use of 3D CAM. (c) Other digital information. (d) Time devoted to CAM preparation.

As seen, an equal proportion of companies do not use CAM (0%) (Figure 5.9b) and consequently spend no time (0%) in CAM programming (Figure 5.9d). Among the other 97 companies that use CAM to some extent, 36% of process planning time is on average spent on CAM programming.

The number of companies that use feature-based CAM stands for 14% of the respondents (Figure 5.10a). Integrating the product realisation chain has been one of the main ventures of CAD/CAM providers during the last ten to twenty years, where PLM has been a focal point. It is therefore of note that only 2% of the companies use any PLM system (Figure 5.10b).

Miscellaneous questions and response

The proportion of companies that uses any process planning performance measurements is 26% (Figure 5.10c). Among these, 66% of the respondents use man-hours as a performance indicator. To a lesser extent, this figure is translated into cost and total planning lead time (Table 5.6 a). Production ramp-up time and quality were rated as process planning performance indicators by 40% and 47% respectively. The chance of bias in this question is however overhanging, since some of the stated performance indicators are common indicators of production performance, but not necessarily applied to process planning. Related to performance indicators of production is the use of C_{pk}. Only a smaller part of the respondents use C_{pk} values. The most common C_{pk} target value is 1.33 (two-thirds of companies). It appears to be more common in larger companies to employ C_{pk}, where the average size of companies with C_{pk} target values is 86 employees (median 10), compared to 21 employees (median of 23) among all the companies that responded. It should be noted however that smaller companies also use C_{pk}.

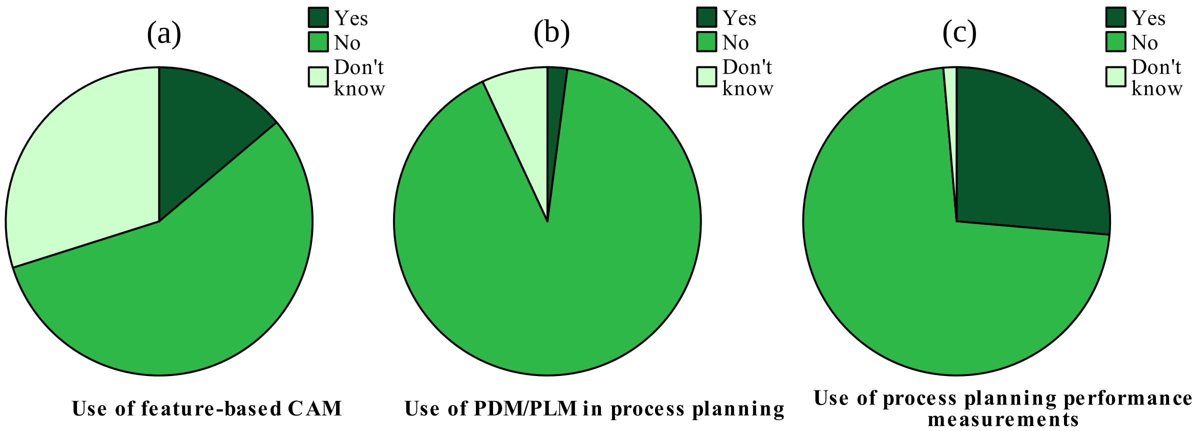


Figure 5.10 (a) Use of feature-based CAM. (b) Use of PDM/PLM systems. (c) Use of process planning performance measurements.

Table 5.6 Response from companies that stated that (a) performance measurements are used for process planning and (b) considered environmental aspects (multi choice).

(a) Performance indicators	Responses N	Percent of Cases
Process planning man-hours	25	65,8%
Number of finished process plans	3	7,9%
Process planning cost	12	31,6%
Process planning time	8	21,1%
Quality in production	18	47,4%
Ramp-up time in production	15	39,5%
Other	5	13,2%
Total	86	226,3%

(b) Environmental aspects	Responses N	Percent of Cases
Energy use	26	40.6%
Cutting fluids	34	53.1%
Noise	15	23.4%
Material use	52	81.3%
Air quality	13	20.3%
Scrap rate	40	62.5%
Machine downtime	30	46.9%
Other factors	13	20.3%
Total	223	348.4%

In terms of systematic process planning works, various standards can be used as aids to create structured work flows. Table 5.7 gives an overview of these standards and their respective usage. 42% of the companies do not use any standards, followed by 21% that use ISO 90001/4. 18% state that other standards are used.

With respect to deficiencies and problems identified in process planning, 43% of the companies state that no particular problems are perceived (Table 5.8 sum of "no problems" and "do not know"). It is worth noting that 31% of the companies experience competence problems, although it is not stated what these problems relate to. Further studies are consequently needed to investigate whether problems are universal or individual and whether they concern knowledge of metal cutting, software skills, machines, procedures etc. Related to the latter are companies that experience problems with systematic work.

The companies were also asked whether environmental aspects were considered during process planning and 44% claimed so. Of these companies 81% stated material use as a regarded environmental impact (Table 5.6 b). Cutting fluids and energy use were cited by 53% and 40% of the companies, respectively. There is a risk for bias in these answers in that scrap rate and machine downtime are stated to be commonly regarded as environmental concerns, although they are in reality more likely regarded as quality and cost problems.

The size of the companies that responded differs significantly, ranging between 1 and 500 employees. The bulk is SMEs, where 95% are small companies (less than 50 employees). The others are of middle size, except one company with 500 employees. The average size is 21 employees (median ten). The number of persons working with process planning is of course reflected in the size of the company, but here 70% of the companies have three persons or more that work with process planning.

In the responding companies, 17% have primarily one-piece production and the majority has mixed production volumes. 27% have on average larger volumes than 100 parts/batch. These figures are based on 99 responses. The product price in the companies varies between 5 SEK and 7 MSEK (based on 44 responses), and thus there is a large variation in prerequisites for production. More details on the characteristics of the respondents are found in Appendix D.

Table 5.7 Use of standards during process planning (multi choice).

Standards	Responses N	Percent of Cases
ISO 9001/4:Quality management systems - requirements	38	26.4%
ISO 14001/4/5: Environmental management systems	23	16.0%
Other standards are used	32	22.2%
No standard is used during process planning	73	50.7%
Don't know	10	6.9%
ISO 10303-238: Industrial automation systems and integration - Product data representation and exchange	0	0%
ISO 10303-240: Industrial automation systems and integration - Product data representation and exchange	0	0%
ISO 10303-242: Industrial automation systems and integration - Product data representation and exchange	0	0%
ISO 22400: Industrial automation systems and integration - Key performance indicators for manufacturing operations management	0	0%
Total	176	122.2%

Table 5.8 Problems identified in process planning work (multiple choice).

Problems	Responses N	Percent of Cases
Deficiencies in software	26	18.1%
Deficiencies in systematic work	25	17.4%
Knowledge feedback	27	18.8%
Problem in information retrieval	18	12.5%
Deficiencies in competence	45	31.3%
Other	14	9.7%
No specific problems	48	33.3%
Don't know	14	9.7%
Total	217	150.7%

Factor correlation

To analyse the relation between the responses of the numerical scale questions, two Pearson product moment correlation coefficient matrices were constructed. Since extreme values can have a significant influence on correlation, two tables were constructed, one with the whole population (Table 8.5) and the second with the companies with no 3D CAD in process planning (<2% 3D CAD) (Table 8.6), to verify whether correlations were valid for the whole population or only for parts of it.

It is seen from the correlation analysis that use of CAM is correlated to the use of 3D CAD. This may seem trivial, but it is an important finding since it indicates that the right prerequisites must exist to be able to automate process planning work. It should be noted, however, that the causality is not given and further work is needed to verify whether it is an ambition to use CAM that spurs 3D CAD use or the availability of digital product data which render a situation where it is feasible to implement CAM. The proportion of other digital data shows a less strong correlation to 3D CAD and CAM use, although still significant at the 0.05 level (in companies with more than 2% 3D CAD). Nonetheless, the advance towards increased use of computer aids in process planning depends on the level of digitalisation. There is also a medium/strong correlation between CAM use and proportion of process planning time dedicated to CAM, which appears reasonable.

Other significant correlations, albeit small, are found between the number of people involved in process planning and CAM use and there is a somewhat weaker correlation for 3D CAD use. It can thus only be speculated whether CAM/3D CAD use is a matter of organisational solutions to a growing number of people involved. It is interesting to note between the two correlation tables that, when the respondents with less than 2% 3D CAM are removed, product value appears to have a slight positive correlation to 3D CAD and CAM use but that, when the whole population was included, it instead signalled a non-significant negative correlation. This correlation is extremely uncertain, however, since there are many missing values, only 29% of companies responded. Altogether the difference between the two correlation tables, gives that less strong correlations are found for when the responding companies using 0-2% 3D CAD are removed (Table 8.6). Irrespective of correlation table studied, similar tendencies can be found, except for the case noted above.

In conclusion, this survey complements the situation and findings depicted by the other three surveys, in particular survey 1. The use of 3D CAD product data can be divided into three parts: the companies with no 3D CAD usage, the companies with the bulk of products as 3D CAD models and the third category, which is between the other two, where companies appear to be flexible and situation dependent in their use of 3D CAD data. Possible explanations for this may be type of machines (control system), customers, competency, tradition and/or company culture, but it has not been possible to verify this. The use of process planning performance measurements is limited, where only 17% of the companies document process planning time (man-hours). The company prerequisites (i.e. company size, number of process planners, product prices and production volumes) investigated in this survey could not be correlated to the use of 3D CAD and CAM.

5.1.5 Synthesis of process planning methodology in the metal working industry

As already referred to, Halevi and Weill (1995) (Section 2.1) found that the process planners' work activities are roughly distributed as 15% technical decision making, 40% data, table reading/retrieving and calculations, and 45% text and documentation. This observation was published in 1995 – 16 years ago. During this time, computer aids have developed considerably and computational power has increased many times and the integration between CAD and CAM has increased. The same is valid for the possibilities for model-based information management through PLM and other data management systems. During this time it would have been possible for the industry to have made significant improvements in process planning work, so that more resources could be dedicated to decision making. Despite the technological development since 1995, it could not be observed in the surveys conducted that any radical shift has occurred in the industry that substantially redistributes the resource allocation. In survey 1 information management was pointed out as a major inefficiency of process planning, where a substantial proportion of time was dedicated to data reconstruction. It must be mentioned however that this was not the main aim of these surveys, so no definite data were specifically collected on resource allocation. The conclusion must be that the situation appears to be rather similar to the one observed by Halevi and Weill.

In general, the surveys conducted show that there is a need for aids (technical and methodological) that address this issue. Since survey 2 pointed in a similar direction in terms of process planning computer aids, there appears to be a need to implement systems where data can be reused effectively so that tedious manual work can be automated. By using CAM systems rather than manual NC programming, the gain is two-fold. First, part geometry data can be seamlessly integrated (if CAD/CAM systems are integrated). Second, less work is dedicated to tool path calculations and program writing. These measures will potentially positively impact the process planning lead times and the quality of machining processes. PLM systems target the working methodological and information managerial aspects of process planning. However, the overall efficiency of these systems (at least in a short term perspective) may be questionable, since they often require substantial investments and administrative resources, which particularly for SMEs, can be heavy costs to carry. There is consequently a need for cost efficient systems that contain the basic functionality, without being too complex. It is therefore important to develop strategies for how to advance towards digitalisation of the company (internally and externally) to enable the use of more advanced computer aids. In this light it is vital to develop closer cooperation in the supply chains so that CAD models can be the principal information carrier of product data.

The way that companies work with process planning aids could not be correlated to any of the identified company prerequisites (survey 1 - hypothesis 2 and survey 4 - factor correlations). One possibility is that the efficiency and the use of aids depend on factors other than the ones included in the studies, where one possible explanation is the human factor. The people involved in the process planning organisation or management may be the driving forces behind focusing on process planning aids and efficiency - or not.

Although the companies investigated claim to have a good understanding of the process planning function's influence on company objectives (survey 3), there was a lack of a correlation between perceived process planning efficiency and the proportion of information retrieval as part of the total process planning time (survey 1). This suggests a need for development of a quantification/measurement system of process planning performance. The exact content and scope of such a performance measurement system has not been treated in this thesis and is primarily an issue for the individual organisation. This is further discussed in section 6.1.1.

The surveys performed suggest the development of a stronger focus on understanding the importance of process planning for meeting company objectives. This is imperative for companies that do not have their own design responsibilities, since they have few other means to compete besides process planning and efficient/effective manufacturing. Survey 3 indicated that performance measurements as a method for gaining process knowledge are rather limited. If production is not extensively measured, can it be assumed that other operations are more quantified in terms of performance measurements? The answer cannot be scientifically proven by these surveys, although the findings point in the direction that the companies do not have more knowledge about the performance of other operations.

The above named information management problem also motivated studying the importance of the quality of data and information used during process planning. If data are reused by the process planner (as e.g. production runtime data) it is essential that the data and information are beneficial to manufacturing performance. The importance of having the right information, indicating performance that is vital for the organisation, cannot be underestimated.

5.2 Process planning for robust machining

To assess process planning effectiveness, process capability was selected as one performance objective to study in greater depth. Thus, an investigation was set up based on an approach where the use of production runtime data in the form of PCIs during process planning benefits the development of robust CNC machining processes. However, to enable efficient and effective use of PCIs, it is vital that these are measured correctly so that the intrinsic machining process capability is captured. It is otherwise likely that no real gains will be achieved in terms of increased capability and reduced CoPQ.

The research work aimed at describing the industrial problem by studying two different types of companies and their use of PCIs and, where possible, analysing retrieved runtime data from the machining process. Thus no additional capability studies were conducted except for an analysis the companies own data. A central part of this issue is the process capability criterion: whether it is the process that is intrinsically capable or whether it is capable because of in-process controls (such as manual measurements or automatic probing etc.). The following research questions were set up to address this problem:

- How are PCIs measured in the studied companies?
- What do PCIs represent in terms of process capability in the studied companies?
- How can PCIs be employed in process planning to achieve better production processes?
- What are the implications for different ways of capturing process capability in terms of production development for increased automation?

The research questions, intended outcome and research method are summarised in Figure 5.11.

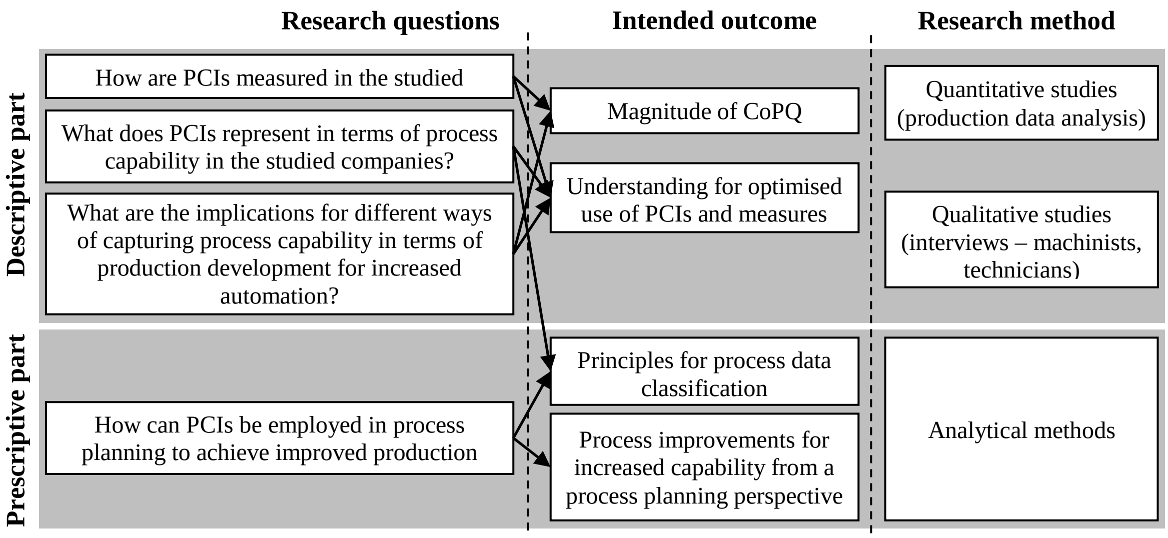


Figure 5.11 Overview of process capability investigation.

5.2.1 *Cost of Poor Quality study*

The costs associated with non-capable processes can be modelled using a CoPQ model. This type of model is, in theory, vast in order to be complete. This means that, in practice, these models become cumbersome to feed with reliable data if they are not reduced in scope.

The following part will explain the CoPQ model developed for machining process I in company A (Table 5.11 and Figure 5.12). The scope was strictly limited, where only aggregates of the main processes were used and probability data were based on C_p/C_{pk} values as taken from in-process inspections with a gauge. Values for each operation are given in Table 5.9. The probability for an event based on the sigma level can be expressed as in equation 5.1.

$$P = \emptyset(x_{max}) - \emptyset(-x_{min}) \tag{5.1}$$

The relation between C_p and C_{pk} matters if these values are different for a given process. If they are similar, then the process is centred to the process target value. Most often the process is not centred, thus resulting in different values of C_p and C_{pk} – it is therefore vital to always present both indices. This also implies that the process probability density for a centred and a non-centred process differs. To calculate the probability that a randomly produced part is within specified tolerances based on C_p/C_{pk} the unit normal deviate, x must be calculated for the upper and lower specification limits. This is then used to calculate the standard normal cumulative distribution function, $\phi(x)$, as is seen in equation 5.1. Equation 5.2 can be used to calculate x_{max} and x_{min} and is derived in Appendix E.

$$x_{max/min} = 3C_p \pm 3(C_p - C_{pk}) \tag{5.2}$$

For lower C_p/C_{pk} values this results in larger errors if the probability is based on C_p alone and the error also increases with larger differences between C_p/C_{pk}.

For the CoPQ example used here, the situation is simplified to accumulate all machining operations into one machining block (OP-X) and associated inspections, as illustrated in Figure 5.12. Inspection points both consist of an activity (and its associated cost) and a gate with an associated C_p/C_{pk}. All cost-incurring activities and probabilities are explained in Table 5.9 and Table 5.10.

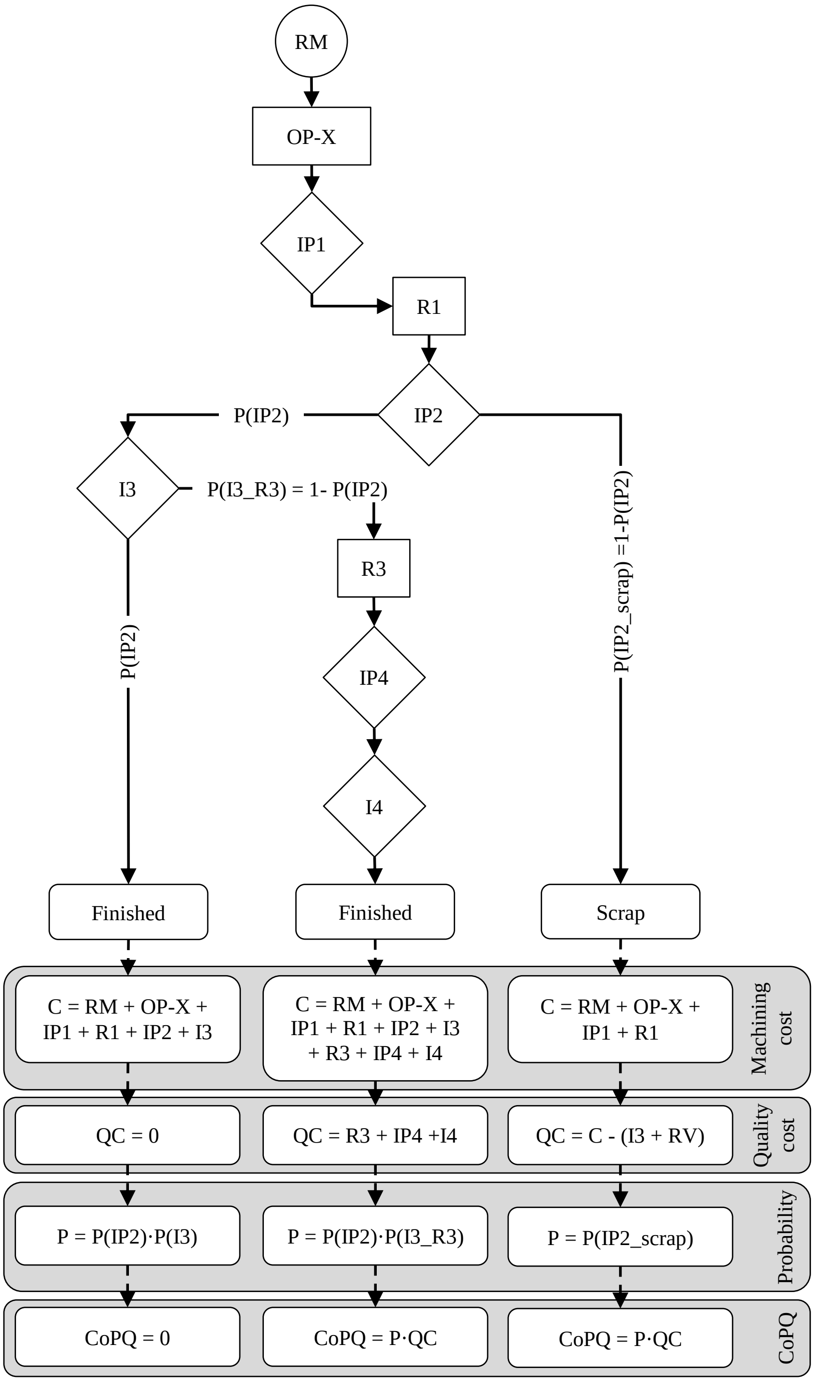


Figure 5.12 CoPQ model for company A and process I.

CoPQ for the current process is calculated as illustrated in Figure 5.12, where the individual CoPQs at the bottom are summarised. Each CoPQ corresponds to a certain process outcome from which the associated cost and the probability for this outfall are multiplied. Figure 5.13 shows the calculated CoPQ for a number of operations (Table 5.9) in relation to appraisal cost, i.e. in-process measurements for process I company A. The appraisal cost is based on automatically logged machine down time specified to in-process controls. The calculation of this cost is given in Appendix E (equation A.3). The calculation of CoPQ as illustrated in Figure 5.13 for different C_p/C_{pk} values is based on real production runtime data and estimated costs by the company. However, for reasons of secrecy, the cost rates and specific times used are not included here. As seen in Figure 5.13, the break even between CoPQ and appraisal cost is found at C_{pk}=1.2. Beyond this point the process capability is good enough so that CoPQ is lower than the appraisal cost. Does this then imply that appraisal activities are unnecessary? The answer is no, but possibly yes – based on the data provided in the specific process no definite conclusion can be drawn. However, if runtime data had been saved differently, it would have been possible to achieve more certainty in the answer, since it is not the intrinsic C_{pk} of the process, but a corrected one that is found in the saved runtime capability data. In relation to Figure 5.12, this means that the C_p/C_{pk} value of IP1 would be required, which would then correspond to the intrinsic process capability. This highlights the need of finding the intrinsic capability of the process.

Table 5.9 Calculated for 8 operations of process I, company A

Op.	C_p	C_{pk}	Tol. Width *(USL-LSL)*	Mean *(μ)*	Std dev. *(σ)*	Max (Min) Sigma level, σ	Probability *(P)*	Theoretical # faulty parts/300 parts
1	2.43	2.39	0.1	44.85	0.014	7.4 (7.2)	0.9999999999996	1.26E-10
2	1.75	1.67	0.1	2.69	0.019	5.5 (5.0)	0.9999996921079	0.00009
3	1.40	1.34	0.1	6.80	0.024	4.4 (4.0)	0.9999668091055	0.00996
4	1.58	1.27	0.1	2.97	0.021	5.7 (3.8)	0.9999264652045	0.02206
5	1.43	1.26	0.075	70.76	0.017	4.8 (3.8)	0.9999164062432	0.02508
6	1.29	1.21	0.1	6.09	0.026	4.1 (3.6)	0.9998352156289	0.04944
7	1.37	1.11	0.1	50.83	0.024	4.9 (3.3)	0.9995639523012	0.13081
8	1.16	0.98	0.1	4.02	0.029	4.1 (2.9)	0.9982664038494	0.52008

Table 5.10 Explanation of notations in relation to Figure 5.12.

RM	Raw material
OP-X	Main machining operation
IP1	In-process inspection
R1	Rework
IP2	In-Process inspection
I3	Final inspection (CMM)
R3	Rework
IP4	In-process inspection
I4	Final inspection (CMM)
RV	Scrap value
P(IP2)	Probability to pass in-process inspection (C_p/C_{pk} machining process)
P(I3)	Probability to pass final inspection (C_p/C_{pk} final inspection)
P(IP2_scrap)	Probability not to pass in-process inspection
P(I3_R3)	Probability not to pass final inspection

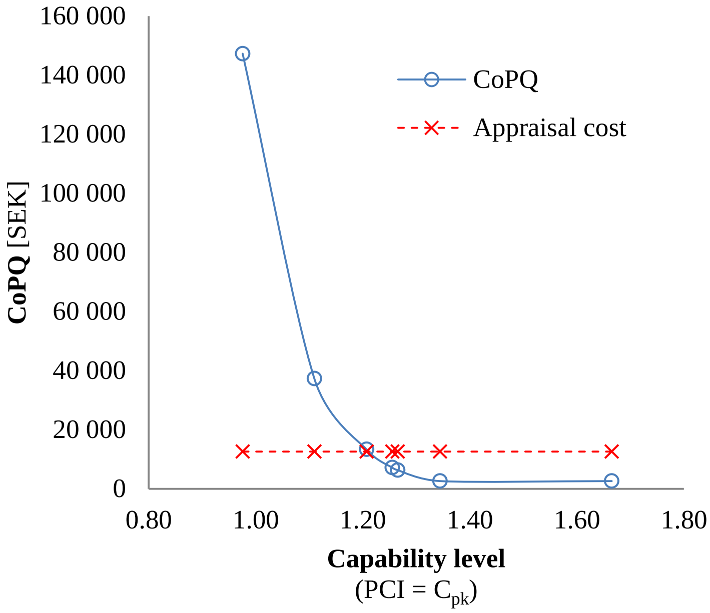


Figure 5.13 Plot of CoPQ and appraisal cost for investigated company A, process I based on production of 300 units, a common annual production volume for the part.

Appraisal cost and prevention cost are often distinguished, where the former refers to preventive actions taken in the physical environment around the machine and is often in-process control methods, e.g. machine stop to measure and give coordinate compensations according to measured values. Prevention cost refers to the preventive actions taken during design work or process planning in order to improve process capability. Reliable process data are important to make preventive actions effective. This is the reason why capability measures of the intrinsic process are essential.

Below a few examples of relations between CoPQ and appraisal costs are given. Figure 5.14-A shows one example in which the capability of the process is improved (here shown as reduced CoPQ) by increasing the number of appraisal activities. This approach may be beneficial, but there is a risk that appraisal cost exceeds the cost that it strives to prevent. Figure 5.14-B shows a situation in which the process is intrinsically improved (e.g. through a better machining strategy, selection of tools or machining parameters), which leads to higher capability and reduced CoPQ as well as a reduced need for process support, and thus reduced appraisal costs. A third case can be seen in Figure 5.14-C, which is exemplified by one of the companies studied. Company A and process I earlier had one supplier of workpieces for the process (Figure 5.14-C, point 1) but changed its supplier some time back. The new supplier's workpieces are cheaper but have a larger variation in material properties, which inflicts lower process capability during machining so that appraisal activities are required (Figure 5.14-C, point 2). Initially this can be regarded as a flawed decision in a production perspective. However, if the operator supported the processes to the same extent as prior to the change, the decision cannot as easily be dismissed, since the appraisal cost during the two machining cases are basically identical. It must however be assumed that the final product has the same quality level in the two cases.

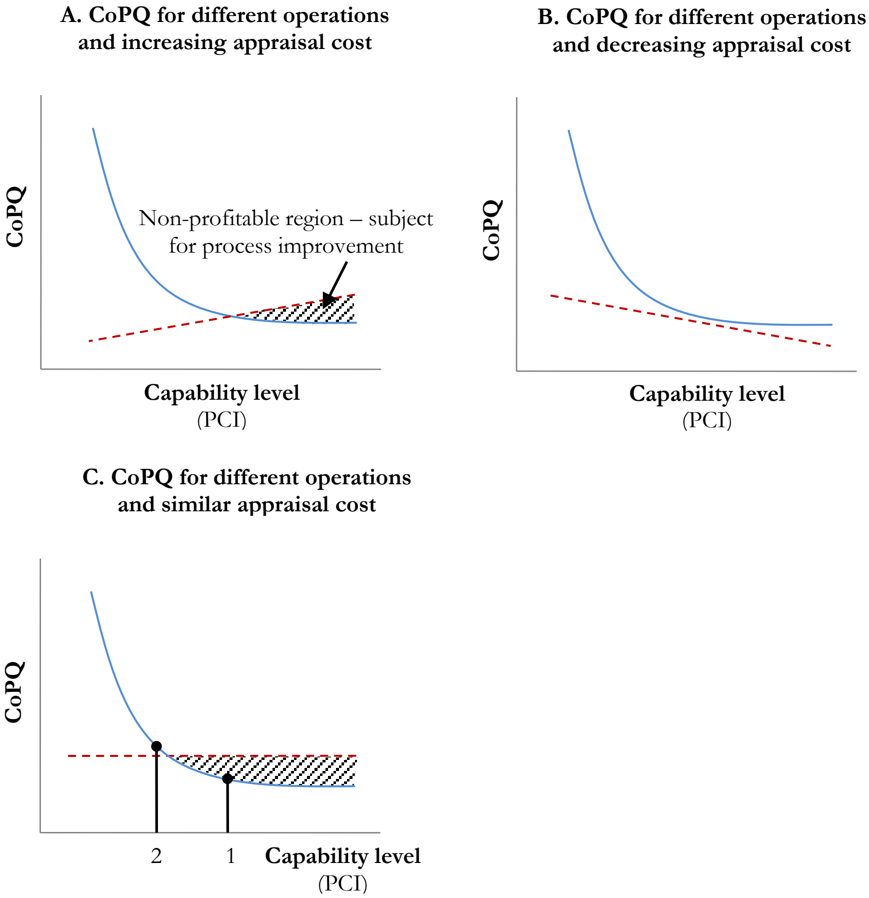


Figure 5.14 Example indicating the relation between CoPQ and the appraisal cost.

5.2.2 Company case studies

Hereunder follows a short discussion and presentation of two companies and three processes in relation to process capability measurements and the usability of these. Production characteristics for each process are compiled in Table 5.11.

Company A

The company is a large sub-supplier to the global aerospace industry. The production is characterised by a high share of CNC machining of many materials with low machinability (e.g. nickel base alloys and titanium alloys). Products are often large and thin-walled, which restricts the machining parameter selection. Dedicated fixtures are used to reduce workpiece vibrations. The aerospace industry is controlled to a large extent by legislation regarding the traceability of individual components, which means that there are requirements on data storage concerning the production history of each component and its runtime data. Altogether it is a complex process planning situation that is resource intensive, and new processes may require several man-years of process planning work.

Two processes were studied in the company. Processes I and II both comprise machining of thin-walled nickel-based components, where the final dimensions are difficult to attain due to small tolerances in relation to overall component dimension. This is due to deflection of the workpiece. Common for the two processes is that all product measures are verified by CMM after machining is finished.

Process I has some 60 specified functional requirements, mainly dimensions of height and diameter. Figure 5.15 illustrates the process flow to turn one such feature in a vertical lathe. The machining procedure for all defined measures follows the same procedure, where the machine is stopped at a certain distance from the nominal measure. The operator next manually measures the feature with a gauge and calculates the compensation so that the nominal value can be reached. To the operators' aid is a chart containing previous measures, numerical compensations and outcome. After compensations are given, the next machining block is started and stopped once again when the compensated operation is performed, so that the operator can verify the measure. The next operation block is then started if the measure is within tolerances; otherwise additional compensation is required.

The final outcome value of each feature is saved in the common database and can be retrieved at any time, with the exact measurement data, feature and part ID number. PCIs are calculated on the basis of these data. The initially measured values are however not saved in the common enterprise database but are only collected in a chart to enable follow-ups if there are problems in order to aid the operators. These data, which are not systematically saved, indicate the intrinsic capability of the machining process without manual appraisal from the operator. It would be valuable to systematically save these data and use them as a basis for PCIs so that the intrinsic capability is captured, which aids operation selection and assessing the need for appraisal activities.

Since there are many in-cycle gauging machine stops, a substantial part of the machining process is dedicated to non-material removing activities. The actual material removing time for process I corresponds to 57% and in-process gauging 11%. The rest is other manual work activities. There are consequently good incitements for making process capability improvements for cost reduction (appraisal and machine down-time).

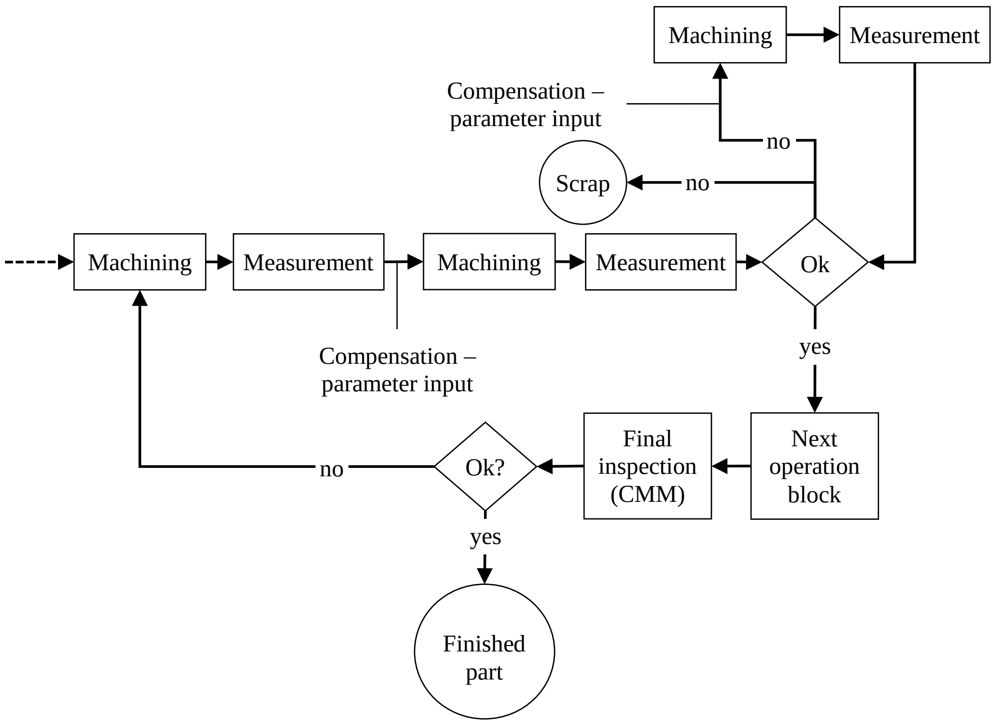


Figure 5.15 General process flow for machining of one feature for process I, company A.

Machining process II follows a similar sequence of events but with the primary difference that the bulk of measurements and compensations is performed by automatic probing cycles and compensations are automatically calculated by NC program logics. This means that no operator is continuously needed. The standard probing/compensation cycle involves three measurements and two coordinate compensations to attain the nominal dimensional value. One of the benefits of this concept, besides reduced time for measurements/compensations, is that probed measures can automatically be saved in a database and are easily accessible. The ease of access of process data is hidden by the fact that, first, probe values from the same feature have no common name convention so that it is difficult to easily present the capability of the process for a specific feature. Second, the target values for each feature have different tolerance widths, which means that, when presented as C_{pk} values, the intrinsic capability is different from what the values show. A better alternative would be to use the same tolerance widths for all measurements required on the same feature and accept the fact that C_{pk} will be lower, but with real meaning to the values. The real capability can thereby be compared between each probing step.

As presented, despite the vast amounts of product and production runtime data for each of the two processes, data cannot readily be used for indicating the intrinsic process capability, i.e. process capability without interferences from in-process control (i.e. appraisal activities).

Company B

The company is a medium size subsidiary of a global enterprise and supplier to the heavy automotive industry and an ODM with construction and production responsibility for hydraulic components. The company was selected to represent a general SME company of the Swedish metal working industry. The products delivered have high demands on quality, and tolerances are tight, down to 2 µm. Production is characterised by small batches with products in defined product families, where the basic features are altered into numerous variants with only small differences within product families. CNC processes include milling, turning, drilling and grinding.

In general there are no in-process measurements and controls are made after machining by the operator either with manual tools or in a CMM. Measurements are taken of random samples from each batch, where approximately 5% of it is measured. Manual measurements are not saved, but all data from CMM are saved. The data are not used for calculating process capability, however, and consequently no PCIs exist. The only capability studies made are when new machine tools are purchased. The company is satisfied with the current quality level and scrap rate, which is regarded as being normal for the manufacturing sector. Parts that do not meet specified tolerances are always discarded. The data from the CMM can be employed to describe the capability of the machining process. However, one in-process measure is made where the operator gives numerical compensations if measures drifts, but this compensation is given only on subsequent parts not on the currently measured one.

In a process planning perspective, new products within the product families are based to a large extent on other products. This means that, often, only dimensions are altered, and an NC program can consist of up to 80% reused program code. This means that there is a significant knowledge reuse but, since no PCIs for processes exist, the capabilities of the planned operations are difficult to judge a priori. The process planner instead *assumes* that the current machining processes are already capable to an acceptable level.

Methods for managing existing and new operations based on process capability level are presented below. First, the use of a hierarchical operation knowledge model is proposed and described. Second, a strategy and decision model based on the operation knowledge model are described and exemplified.

Table 5.11 Description of process characteristics.

	Process I, Company A	Process II, Company A	Process III, Company B
Machine	Vertical lathe	5 axis machine centre	Grinding machine
Production characteristics	A standalone machine dedicated to one product and served by one dedicated operator. Narrow tolerance widths paired with big dimensions coupled with features based on thin and weak structures – makes it difficult to meet tolerances in production. This combined with the fact that subsequent operations often influence the already machined features makes it a difficult machining situation.	Machine is part of a FMS cell, where no single operator is dedicated to machine, but acts on machine alarms – programmed stops and unpredictable stops.	Rotationally symmetric workpiece with small tolerances. Small batch production of ~50 pcs/batch. CNC machine served my one machinist.
Operations	Inner and outer turning operations	Turning, milling and drilling operations. Tool changes are fully automatic and most in-process measurements and compensations are automatic, except for one.	Grinding
# of in-process measures	62	31	1 (not compensated in the same operation)
# of final inspection measures	58	13	2 (shape measures)
Intrinsic process capability measured	No	No	No
Production runtime data saved	Yes (100%)	Yes (100%)	No
Final product data saved (CMM)	Yes (100%)	Yes (100%)	Yes (~5%)

5.2.3 Knowledge model based on process capability data

To enable more systematic process planning, one approach as proposed here is to use production runtime data to reduce the risk for inferior processes and plan for robust machining. Each operation (a certain combination of machine, tool, machining parameters and product feature) must therefore be classified according to process capability based on production runtime data.

This implies that the process planner gains a better understanding of the performance of the specific operation. A classification framework has been developed in this research work as a foundation for the hierarchical knowledge model (see Figure 5.16). The aim of such a classification is to provide a better structure for the decision making during process planning. The higher in the knowledge hierarchy, the fewer variations of the outcome can be expected. However, it is important to note that the exact steps in the model that should be taken may differ between situations and organisations.

The knowledge model should be based on a database where available operations are stored (the structure, type of database etc. is not discussed here, but a conventional PLM system is a possible solution). In a simple form, the knowledge database can consist of different operations and features that are coupled with their respective capability (e.g. C_{pk} value). This means that the process planner is better informed of the actual capability of the specific operation. If the capability is not acceptable for a particular production situation, a different operation must be selected or a new operation designed. Below follows a description of data classification based on operation.

The lowest level (Figure 5.16 level 0) of knowledge is obviously the case when no quantifiable knowledge or data exist for a specific operation. This may be because the process planner is new on the job or not familiar with that particular application or operation. This situation must be managed; otherwise the outcome will be unknown. Accordingly, the process planner must take due actions to acquire the appropriate data, i.e. advance in the knowledge hierarchy.

Levels 1-2 (Figure 5.16) are conventional steps to take in order to gain process knowledge. Machining parameters taken from handbooks or tool manufacturers' data sheets are often given for large intervals; hence it is the planner's task to select machining parameters to be used. This renders a situation where the outcome can vary substantially, and thus the process capability can differ substantially. To gain more knowledge, scientifically published experiences may be used, where more details on outcome and setup are given. One problem here is that it can be difficult to find applicable operations. Consulting colleagues is often one way to move forward, assuming they exist and have the required knowledge. It is not unusual that companies stop at this level (especially if only a few parts are to be produced) and run the process under the surveillance of the operator.

On the next level (Figure 5.16 level 3), analytical models, calculations and/or simulations may be used to enhance operation knowledge. It can be costly to run machining tests for certain situations, and consecutive analyses may also be difficult and costly. For these situations, finite element analysis or computational fluid dynamics simulations may be feasible approaches, although unconventional in industry. It usually requires critical products and high CoPQ. CAM simulations and collision simulations may also be conducted at this stage.

The lower levels (Figure 5.16 levels 0-3) cannot provide process capability data. In order to get this, physical machining must be performed, either through machining tests or in actual production.

The higher levels (Figure 5.16 levels 4-5) of knowledge refer to data that are extracted from a company's own tests under the specific circumstances of interest or data retrieved from former manufacturing operations under identical circumstances. The type of available process planning data influences the safety margin in the machining operations, so that machining parameters can be selected to increase process rate (hence decreased CoPPR). Smaller safety margins are needed if data are reliable, which will lead to more robust operations and lower CoPQ.

In contrast, it is not an appealing alternative to solely rely on safe processes (i.e. known processes with predictable and reliable output), since process improvements can only come as a consequence of from certain risk taking, i.e. trying new machining strategies, tools and machining parameters. However, these risks must be properly assessed. The importance of having effective process planning methodology is underlined by the continuous flow of new production technology (machine tools, cutting tools, machining strategies, etc.) that potentially contributes to performance improvements. A change of technology can be considered to be a new operation types, and hence should be treated as such.

Another issue that the process planner must assess is the trade-off between known operations and new operations, where a potential high process rate may result in low capability levels and consequently to high CoPQ and high total cost. It is therefore important to have a strategy for how to manage these situations and develop systematic workflows to aid the individual process planner with a methodology to manage selections and decisions during process planning. It should also be underlined that operations should be classified according to intrinsic process capability.

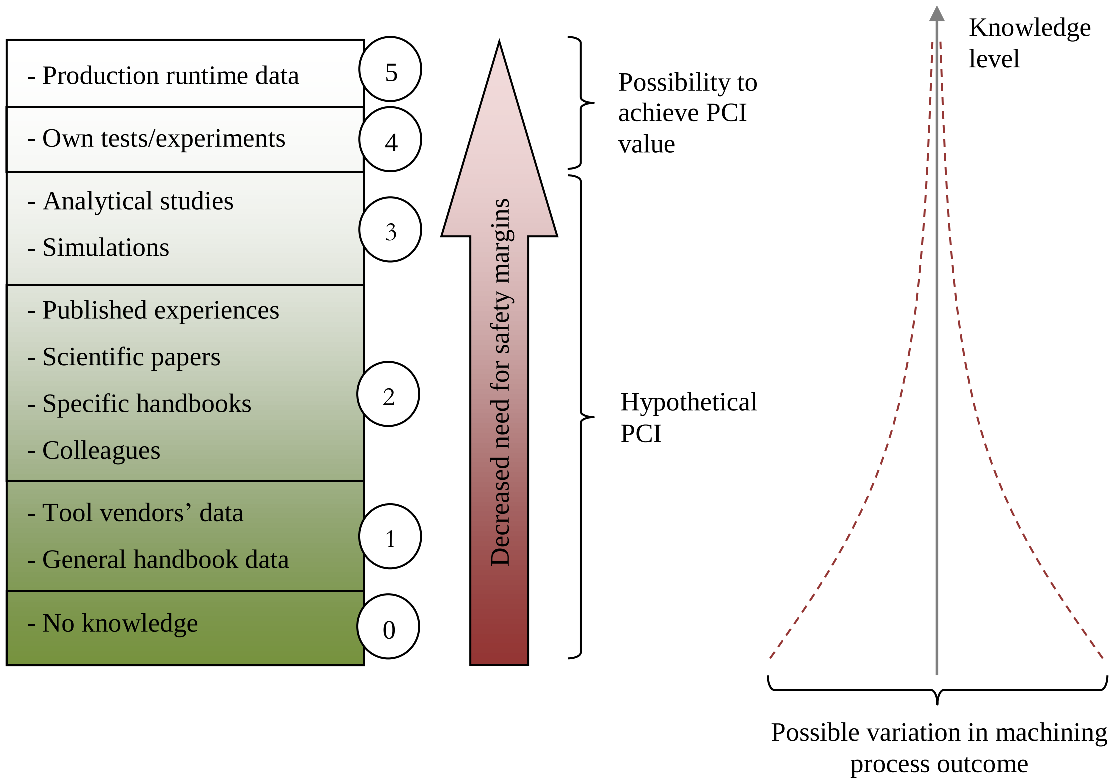


Figure 5.16 Example of process capability classification based on process knowledge.

5.2.4 New operations and use of runtime capability data

If operations are new or unknown to the process planner, there is no former information to rely on, and the process planner must thus tread into unknown domains. Consequently, there is a need for a methodology to efficiently and effectively increase knowledge.

New operations can be radically new (innovative), where there is no existing previous experience or merely alternations of known operations. The time and resources needed to gather to reach an acceptable knowledge level differ depending on the level of previous knowledge and similarities to known operations. If the capability data are obtained from runtime data, their suitability must be assessed for the specific operation, and if they are obtained from experiments, the PCI value should be presented in the form of a confidence interval rather than as a single value (see section 3.2.2).

A risk assessment (such as FMEA) must be based on the probability for the event to occur and the cost it would inflict. Accordingly, greater risks can be tolerated in low value production than in high value production.

The learning curves for new operations have different appearances, but some commonality exists. Figure 5.17 illustrates a general learning curve for process capability knowledge. In order to gain knowledge about process capability, resources must be invested in extracting the appropriate knowledge. Figure 5.17 should be understood in the context of Figure 3.6 and Figure 3.4.

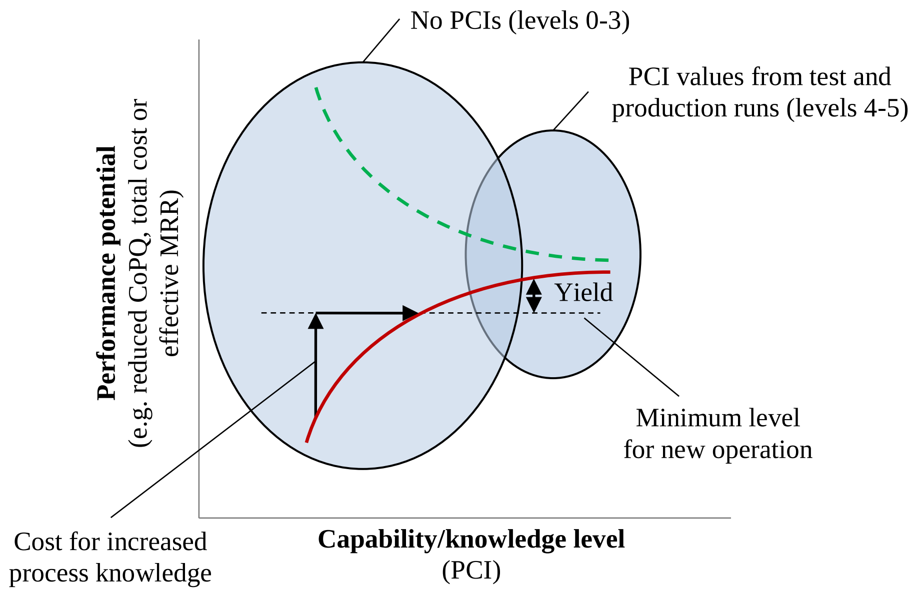


Figure 5.17 Prediction of process capability level in relation to potential production outcome.

It can be argued whether process improvements are part of regular process planning work or part of production development. Here they are treated as integral parts. Redesigning processes and selecting machines, tools and machining parameters previously unknown to the process planner must be considered part of process planning; otherwise the planner would only carry out highly predictable clerical work. If no innovative machining exists, then decision making is simplified as well and it is more easily automated. However, to enable competitive manufacturing, there is a need to make more advanced decisions where the outcome is more uncertain, and thus a need for humans (or at least highly intelligent systems and algorithms).

Different industries have different possibilities for redesigning individual operations. For example, the aerospace industry manufactures advanced products at low volumes, which often leads to conservative process plans, where the chief aim is often to reduce scrap levels, preferably to zero. This is however achieved at reduced process rates.

Different industries are often associated with different manufacturing systems. The manufacturing systems' requirements must also be fulfilled and overall process capability must be regarded. In high volume production with tact requirements, a robust machining process is essential since breakdowns and unplanned stops influence the whole manufacturing system and are thus costly. Under those circumstances there is little possibility to gradually ramp up production. Process capability must be high immediately when implemented and a high PCI value must be guaranteed at that stage.

5.2.5 Analysis of companies from a process capability perspective and decreased operator dependency

There is a significant difference in the two studied companies between the amount of data available and what is measured. However, it is not only the number of measurements taken that differs, but also how the data are stored. The aerospace industry for example is required to collect and save data on a number of product parameters for a certain period of time. The other company studied logs and saves measurement data systematically to a lesser extent. Products are inspected and thereafter approved or rejected, but data are not always stored in a database for future use. This implies difficulties in making process classifications based on production capability data.

A first step would therefore be to initiate a data collection and storage program and undertake capability assessments of these data. Productivity improvements are difficult to achieve if no systematic analysis of production data is carried out. The next step to take is data classification based on the capability level. In this perspective the capability data should be categorised according to the feature and type of process they represent, in order to set up a library of features and their respective capability level so that more informed decisions can be made during process planning.

However, no systematic use of PCIs during process planning could be found in either of the two companies. Using the PCIs in company A in its present state for classifying machining operations could lead to erroneous decisions since the intrinsic capability of the machining process is not encompassed. The basic strategy for improving current processes must be to initially act on inferior processes with low PCI values. Since the advancement towards higher levels of automation in many cases is desired in order to cut production costs, which also was an outspoken ambition in company A, a thorough understanding of process capability is vital. It is therefore important to study the implications that different ways of measuring capability have on the understanding of the possibilities for increasing the automation level and accordingly take corrective actions. Certain levels of automation require certain levels of process capability in order to be robust. The values of measured PCIs can provide information about the prospects for automation of machining processes. Lower capability levels require in-process appraisal activities, whereas higher enable increased autonomy of the machining system, and thus increased automation levels. In order to advance towards fully automated machining processes, high PCI values of the intrinsic process capability are necessary. This means that measures must be taken prior to any appraisal activities of the process have been made. This will give information about the possibilities to disconnect operators from the process.

If the intrinsic process capability is not captured, then data will only give the resulting performance, which is a combination of the operator's skills and the capability of the machine and process planner's capability. The intrinsic capability is a necessity for indicating the capability of process planning to manage the current production prerequisites. It is also possible that appraisal activities during machining are used, even though they are not needed in a process capability perspective but the used simply because the right data are not readily available in the current production system. This leads to higher costs and underlines the importance of having standardised capability measurement routines, so that anyone who uses the data can interpret the capability data unambiguously represented. This reasoning is valid for production organisations where the aim is to advance towards decreased operator dependency, i.e. fully automated CNC machining processes. A possible automation strategy for machining operations based on the level of capability should include the following steps:

- Define the desired level of automation;
- Measure the intrinsic capability of all operations critical for meeting product specifications;
- Define the minimum level of PCI to meet a defined level of automation;
- Focus improvement activities on operations below the minimum PCI level.

Regardless of the striving for high automation levels in production and the extent of advanced process planning aids, it is always relevant to define what a "good" operation is, which can work as a target value for other operations. The reasoning as presented here on process capability should be seen as one way forward in the attempt to improve competitiveness by improving capability and thereby decreasing appraisal cost, CoPQ and shortened ramp up times in metal cutting processes.

Higher levels of automation and process capability are examples of demands that are increasing in importance, which influence process planning. The next section addresses a different kind of what can be considered new demands, namely energy efficiency as part of reducing the environmental impact from machining.

5.3 Process planning for energy efficient machining

This section of the thesis will investigate the relationship between electrical energy use in CNC machining and total machining cost and its implications. To be able to achieve environmentally benign manufacturing it is important to have methodologies and strategies that are legitimate and valid to make efficacious decisions. Since process planning is largely an activity to merge various demands into an optimal solution (process plan), new and changing demands must be managed.

The approach suggested here is based on a cost model, which includes cost associated with machining and corresponding variable energy cost, which is typically excluded in machining cost calculations. The machining cost is then compared to the actual energy use during machine operation for a number of machining strategies that are experimentally tested to achieve real machining data on electrical energy use and tool wear. The cost model and experiments constitute the basis for the analyses of what the implications are of increased energy reduction demands on machining from a process planning perspective.

5.3.1 Cost model description

The cost model is divided into traditional and non-traditional cost components (see equation 5.4). The traditional cost components are based on conventional calculation methods from handbooks and descriptions of these are given in Appendix F. The non-traditional components refer to electrical energy use during machining.

Each cost component is presented with an equation and the constants used are given in Table 1. The model is based on turning operations with indexable inserts. The total machining cost C_M is defined as follows (equation 5.4):

$$C_M = \underbrace{C_m + C_s + C_i + C_t + C_{it}}_{\text{Traditional costs}} + \underbrace{C_{ED} + C_{EID}}_{\text{Non-traditional costs}} \quad (5.4)$$

Where C_m is the direct cost for machine tool and labour cost, C_s the set-up cost, C_i the idle cost, C_t the tool cost, C_{it} the indirect tool cost, C_{ED} the direct electrical energy cost and C_{EID} the indirect electrical energy cost.

Non-traditional cost components

The direct energy is related to the direct power of the machine tool, which is the power that is used to cut a material. The power is built up of loaded and unloaded slide moves and spindle rotations:

$$C_{ED} = E_D \cdot K_E \quad (5.5)$$

Where E_D is the direct energy consumption as measured and K_E is the electrical energy cost per kWh. The indirect energy, C_{EID} relates to the fixed power that remains before and after machine program has been executed:

$$C_{EID} = E_{ID} \cdot K_E \tag{5.6}$$

Where E_{ID} is the indirect energy consumption, which is the measured base load power multiplied by the sum of machining time, set-up time, idle time and tool changing time.

Energy

The following energies are employed to assess the relation between machining cost and energy of machining (equation 5.6), where the total machining energy, E_M, is:

$$E_M = E_{ED} + E_{EID} + E_T \tag{5.7}$$

Where E_T is the embodied cutting tool energy defined as in equation 5.7 and the other as stated above.

$$E_T = \frac{(E_{TM} \cdot m + E_{TC})}{0.75i} \cdot \frac{t_m}{T} \tag{5.8}$$

Where E_{TM} is the energy required to manufacture the tool material [kWh], m is the mass of the insert and E_{TC} is the energy required to produce the coating (e.g. PVD and CVD processes). The constant of 0.75 is estimated as the proportion of faulty cutting edges and is given by Karlebo handbok (Wiiburg-Bonde, 2000) in consistence with the cost for the cutting tool.

Table 5.12 Constants used in the calculations. Values without reference are assumed or calculated by the author of this thesis.

Constant	Value	Unit	Source
B_m	100%		
L_m	40	[€/h]	(Eurostat, 2008)
M_m	5	[€/h]	
N_o	1		
t_s	60	[min]	
N	100		
t_i	0.5	[min]	
K_h	100	[€]	
N_h	400	[€]	
K_i	8	[€]	
i	6		
t_c	1	[min]	
K_E	0.1	[€/kWh]	(Goerten and Ganea, 2008)
CES™	131	[kg CO_2/GJ]	(Eurostat, 2008; Jeswiet and Kara, 2008)
η	34%		(Jeswiet and Kara, 2008)
K_{CO2}	15	[€/tonne CO_2]	(NN, 2009b)
E_{TM}	115	[kWh/kg]	(Dahmus and Gutowski, 2004)
E_{TC}	0.3-0.6	[kWh/tool]	(DahmusGutowski, 2004)

The model does not include any other environmental aspects of machining than the ones related to electrical energy use and the embodied energy of the cutting tool. Thus the environmental aspects of machining are not entirely quantified. The principal environmental aspects during the operation of CNC machines are covered. However, aspects regarding the lifecycle of the machine are omitted, as are work environmental aspects such as noise and dust etc. The blank/workpiece is also excluded from the analysis, since the same blank is assumed to be used for machining of a specific part, which means that the material and the volume of removed material are regarded as constants. The case considered here concerns dry cutting, which means that the environmental aspects and costs of cutting fluids are omitted. The results generated are primarily valid for dry machining only.

Standby (fixed) energy that is not directly related to the machining of the specific part has been omitted. This can be compared to a situation where the machine is turned off, when not used for production. In reality however, machines are seldom turned off. Also poor utilisation and poor process capability etc. contributes to higher energy, but these aspects are also excluded.

5.3.2 Experimental machining case

An experimental machining case study of axial turning operations was developed to provide the model with real data about the energy use of the machine tool and the cutting tool life. The experimental case corresponds to roughing operations, since machining parameter selection is greater, where the main objective is to remove material as efficiently as possible, traditionally at the lowest possible cost, but also from an output rate perspective. Roughing operations typically stand for the bulk of the energy consumption during machining, since most of the material is removed during these operations. Finishing is used to produce satisfactory product quality with regard to surface finish and dimensional accuracy. In roughing, surface finish is subordinate.

A cylindrical part of mild carbon steel was selected as the workpiece, which was axially turned using five different machining strategies based on different combinations of feed rate and depth of cut. The cutting speed was kept constant in all strategies. A new cutting tool edge was used for each machining strategy. The size of the flank wear of the tool was measured in a microscope for each cutting edge and machining strategy. Five runs were executed per strategy to reach the linear phase of the flank wear. See Table 5.13 for data on the experimental set-up.

Table 5.13 Experimental set-up.

Workpiece material	Insert	WNMG 06T308-PP IC9025	Tool holder	MWLNL 2020K - 06W	Machine tool	Colchester Tornado A50
Mild carbon steel <0.25%C	Geometry	Trigon	Approach angle, K_r	95°	Max rpm	4000
	Nose radius [mm]	0.8	Axial rake angle, γ_r	-6°	Spindle max power [kW]	5.5
	Clearance angle,	0°	Radial rake angle, γ_a	-6°		
	Lead angle, K	80°				
	No. cutting edges	6				

The results of the machining experiment can be seen in Table 5.14, where the effective removal rate, the corresponding energy consumption and the tool life for the given operation are given. The effective MRR is calculated as the total volume of material removed divided by the total operation time. The benefit of using effective MRR in comparison to the nominal MRR, based on the machining parameters used, is that the time required for tool repositioning is included. To compare e.g. high-speed cutting strategies (high feed rate, cutting speed and small depth of cut) and conventional strategies, it is more representative to include the increased number of repositions for high-speed cutting. It thus describes the capacity of the process more accurately.

For the experiment, a linear tool wear model was used to extrapolate measured tool wear to the tool life criterion, so that the tool life for each set of machining parameters could be calculated. The experiments were conducted so that the initial non-linear wear progression was exceeded, and the tool life criterion of 0.8 mm was selected so that the final rapid non-linear flank wear progression would not have started. The flank wear of the tools used was measured after five experiment runs, i.e. five machined workpieces.

For each run, the machine tool power from the main connector was recorded. The energy was computed using the Riemann sum of the machine power measured at a sample rate of 300 ms. The direct (cutting and operational) power and indirect power were separated.

Table 5.14 Machining parameters and resulting energy consumption and extrapolated tool life.

Exp.	Principal depth of cut [mm]	Depth of cut sequence [mm]	Average depth of cut [mm]	Feed rate [mm/r]	Cutting velocity [m/min]	Nominal MRR [cm^3/min]	Effective MRR [cm^3/min]	Average energy consumption [kWh]	Extrapolated tool life [min]
A	1	1x13	1	0.1	300	30	28	0.120	41
B	1	1x13	1	0.5	300	150	118	0.055	53
C	3.5	3.5x3, 2.5x1	3.25	0.1	300	105	87	0.077	77
D	2	2x6, 1x1	1.85	0.5	300	300	216	0.042	0.5
E	2	2x6, 1x1	1.85	0.25	300	150	122	0.060	41

Due to restraints in workpiece dimensions, it was not possible to maintain a constant depth of cut in all experiments. If the experimental values of energy use and tool wear are inserted into the cost model, it gives that the dominant cost components are machine tool and labour costs followed by set-up and idle costs. The proportion between and the size of different cost components varies according to machining strategy (Figure 5.18 and Figure 5.19). Set-up and idle costs are non-variable costs, meaning that their proportion to other costs only changes with changing machining conditions. Machine and labour costs decrease with increased MRR. This is due to the increased production rate; the time the part spends in the machine decreased. Tool cost and tool changing cost depend directly on the tool life, which is more complex to estimate a priori and which is why experimental data are often required. In the experimental case exemplified here, the tool cost decreased with the MRR but reached a minimum from which it then increased

(Figure 5.19). For the highest MRR in the experiment the tool fatally collapsed after only 30 seconds, which was a consequence of high process temperatures and cutting forces beyond what the tool could withstand. Theoretically, every experimental set-up will principally render the same type of graph, although the magnitude and proportions will differ.

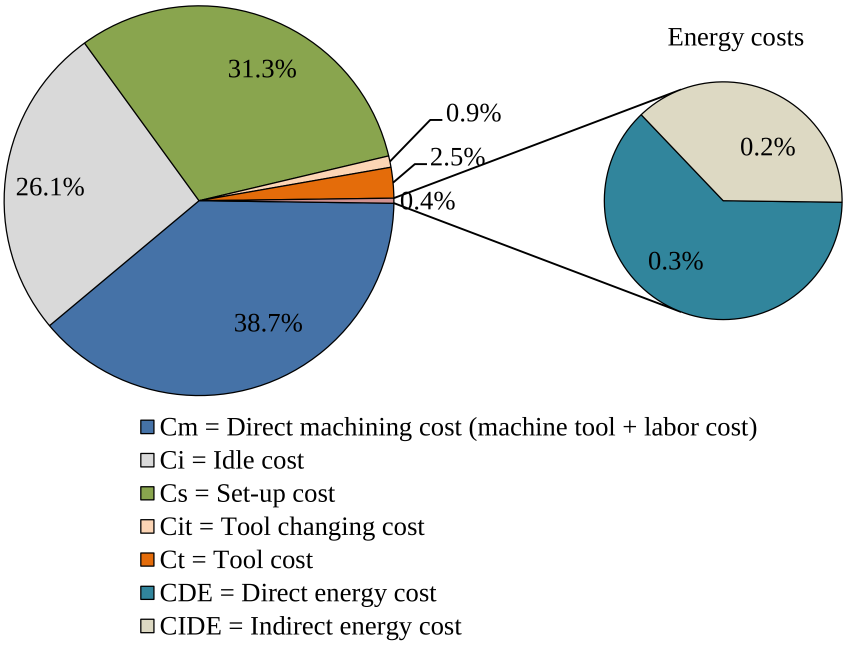


Figure 5.18 Proportion between cost components. The energy related cost components are shown in the cut out pie chart for experimental case E.

The two cost components related to energy consumption are very small in comparison with the major cost components. For the case in which the energy cost proportion was the largest, it still only contributed to less than one percent of the total machining cost. The energy cost is dominated by direct machining energy cost (Figure 5.18). The energy cost is nearly three times higher for the lowest MRR in comparison to the most energy efficient alternative. Albeit small in relation to other costs, the energy cost as such is of importance, since it is a measure of the energy efficiency of the machining process, because it is directly proportional to cost. Its behaviour correlates with the energy consumption and decreases with the increase in MRR (until it converges). Even though the cost of electrical energy is small in relation to other machining costs, on a larger scale it often means a large expenditure for a company; consequently, considerable savings in real value can be made if more energy efficient machining is facilitated.

The time factor is important in a cost perspective. Since labour and machine tool costs are regarded as completely variable costs, the time required to produce the parts becomes crucial.

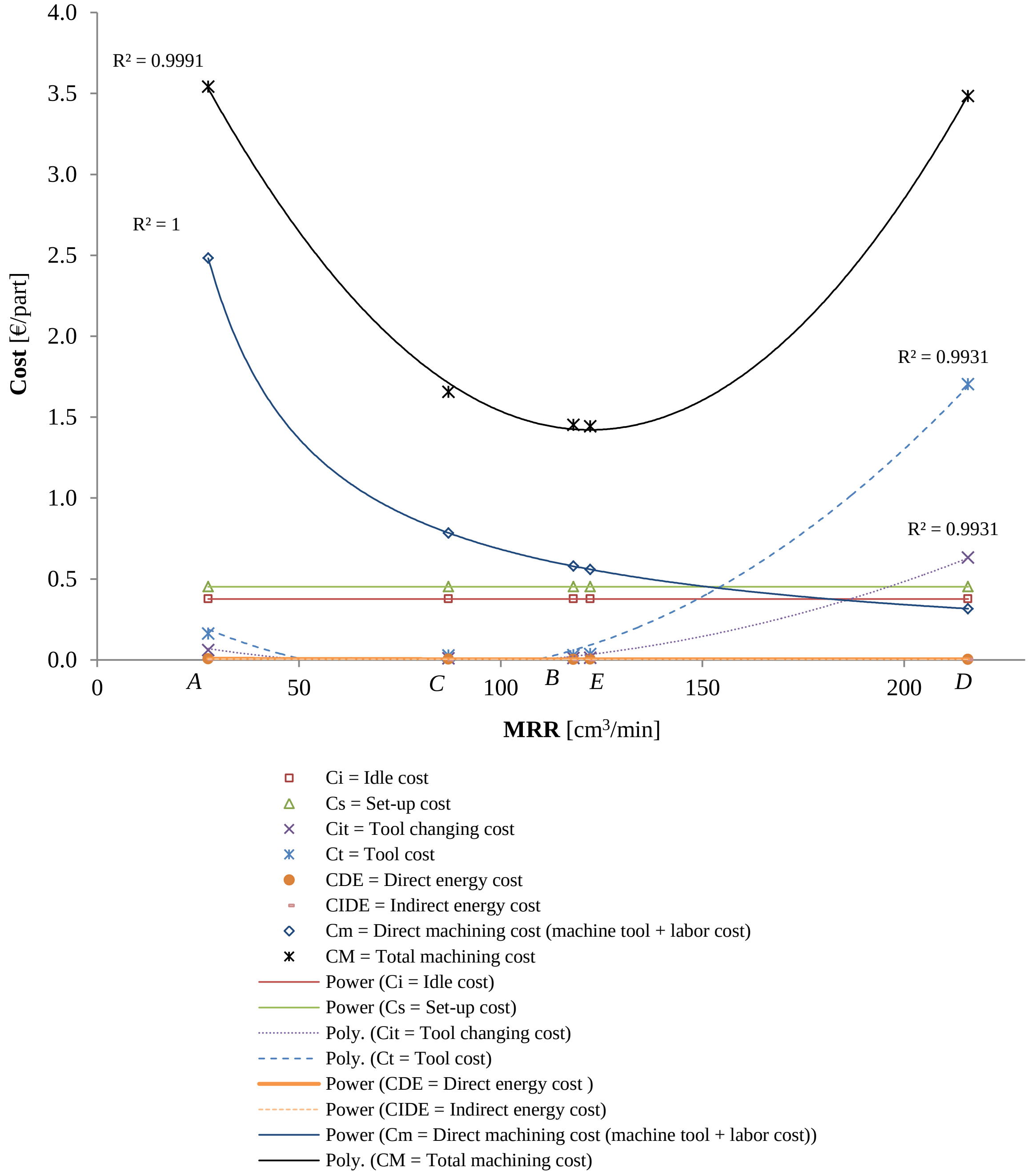


Figure 5.19 Breakdown of costs as a function of MRR.

5.3.3 Company objectives and energy efficiency

All diagrams above are based on monetary comparisons. In order to render a concise understanding of the relation between key company objectives, such as cost efficiency (lowest cost) and production rate in relation to energy consumption, an index must be used, since the parameters all have different units. This was done by relating each value to the maximum value in each parameter's series. The outcome is a ratio between one and zero of all measure points. The parameters are then plotted against the material removal rate as before.

The optimal process window according to total machining cost and production rate approximately coincides with the convergence of the energy consumption curve. This means that, the most energy efficient machining takes place roughly where the highest production rate occurs as well. Beyond this point, more energy efficient machining will come at a rather high machining cost increase, whereas the increase in energy efficiency will generate savings on a smaller scale (approximately 10%). This observation stresses the importance of having a total machining cost perspective, when machining parameters are optimised. If energy use were the only parameter, it would generate a substantially higher total cost, but without any considerable energy savings.

As named above, the specific energy converges towards higher material removal rates. This is a consequence of a larger proportion of direct energy (mainly cutting energy), compared to indirect energy. Since the specific cutting energy is a function of partly material properties and machining parameters and tool properties, the specific cutting energy consumption for a certain setup cannot be further reduced by machining parameter optimisation only.

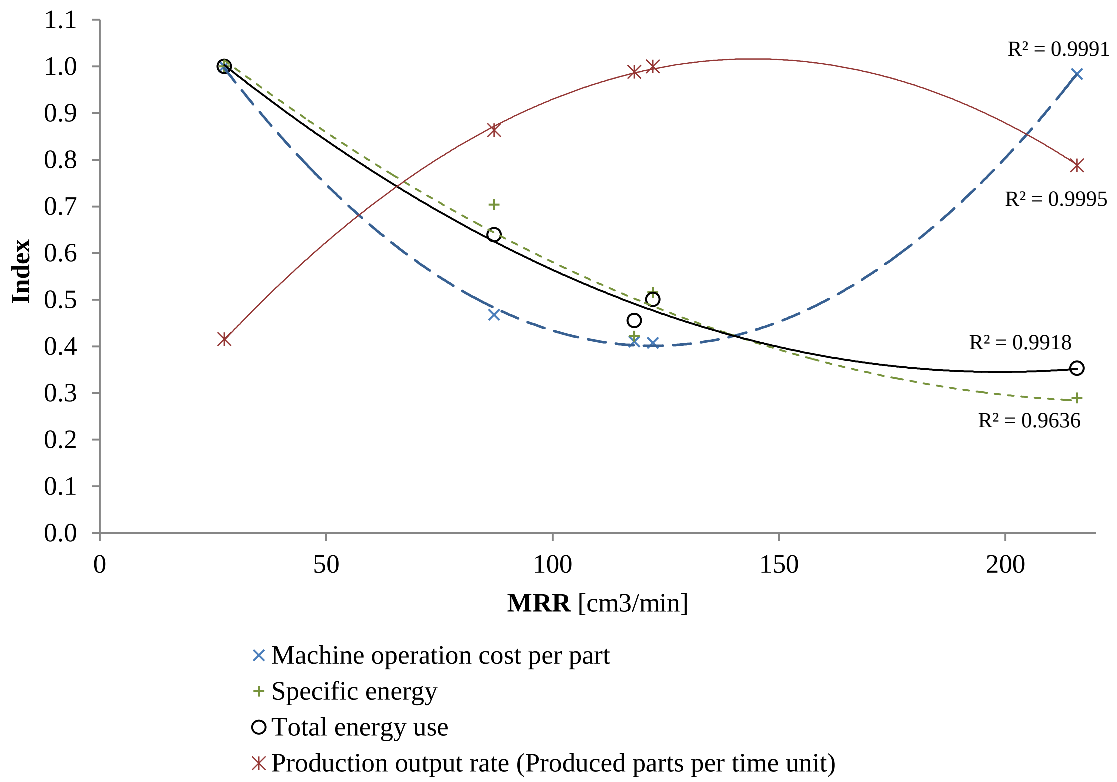


Figure 5.20 Relation between machining cost, total environmental energy use and specific energy.

If the electrical energy consumed by the machine tool is isolated, the conclusion regarding energy efficient machining must be that the higher the MRR, the more energy efficient the machining process (Figure 5.20). This perspective can be defended from one point of view, i.e. the manufacturer's perspective, since this is the energy that is used in the workshop and is thus what the manufacturer sees on the electricity meter and the bill. However, on global level, with expanded system borders, this perspective has its limits, since it does not include the accumulated (embodied) energy in the cutting tool. In general, tool wear increases with MRR, which means that a point must exist where the tool wear becomes too rapid (thus tool life becomes too short) and consequently cannot be regarded as energy efficient in a global perspective, since excessive tool consumption will be the consequence.

5.3.4 Embodied energy in tools

The embodied energy in cutting tools has here been modelled by using values from Dahmus and Gutowski (2004) where the carbide production was stated to require 400 MJ/kg and different coating techniques (PVD and PCD) require 1-2 MJ per coating process and insert. With a weight of 4.0 g for the insert used in the experiments, the embodied energy of the cutting tool is found to be 0.60 kJ/edge (with an insert of six cutting edges and if the higher value is used and there is assumed to be no recycling of inserts). The result is plotted in Figure 5.20. As seen, the difference is small, but when the embodied tool energy (termed total energy use) is included, an optimum can be found. In comparison to when only the electrical energy of the machine tool is regarded (specific energy in the graph) where the energy use converges towards higher MRR. To include embodied tool energy thus appears to be more realistic for setting optimal machining parameters. With increasing embodied energy in relation to MRR, the total energy use curve will move towards the left side of the graph. With decreasing embodied energy, the curve will instead move towards the right, resembling more the specific energy curve of machining operations.

It is important to have reliable data on the embodied energy. The value used in this model is based on the work of Dahmus and Gutowski (2004). However in a personal communication Gutowski (2011), stated that the values are rather approximate. This is an area that consequently needs further work, so that more accurate relations can be identified for the specific machining case.

5.3.5 Internalisation of external costs through carbon dioxide emission trade permits

One possibility for advancing towards a reduced environmental impact of energy use is to internalise the external cost of electrical energy use. The use of cap and trade schemes of carbon dioxide emissions is one method, as has been done by e.g. the European Union and implemented in energy intensive industries. The manufacturing industry in general is thus not included, and this is what is considered in this thesis. However, the individual company can choose to have an internal taxation on energy use so that energy saving incentives are favoured. Voluntarily implementing the EU ETS cap and trade scheme would be one such option, and its influence on machining for increased energy efficiency is evaluated below.

It is studied by using the cost model and adding the cost of the EU ETS carbon trade permit price to evaluate the impact of carbon dioxide emission (C_{CO2}) cost on total machining cost (C_M). To quantify the CO_2 emissions from use of electricity, the carbon emission signature (CES^{TM}) is used as defined by Jeswiet and Kara (2008), which is dependent on the current electrical power supply grid (see Appendix F, equation A.9). Since the CES^{TM} describes the weight of emitted CO_2, the cost of trade permits is included in equation 5.9 to arrive at the CO_2 cost for a specific machining operation.

$$C_{CO_2} = (E_{ID} + E_D) \cdot \frac{CES^{TM}}{1000} \cdot \frac{K_{CO_2}}{1000} \tag{5.9}$$

Where K_{CO2} is the current carbon dioxide emission cap and trade cost per tonne. Values of the 27 European Union countries' power supply grid are presented in Table 5.15.

Table 5.15. The EU 27 power supply grid in 2008 (Eurostat, 2008).

Power source:	Nuclear (N)	Natural gas (NG)	Coal (C)	Lignite (C)	Oil (P)	Biomass (B)	Wind (W)	Hydro (H)	Other (O)
Proportion:	30%	20%	19%	9%	4%	2%	2%	10%	2%

Figure 5.21 shows only the energy related costs as a function of MRR of the machining case. As seen, the C_{CO2} cost is only a fraction of the other energy costs, which in turn are small in relation to other machining costs and does not constitute a factor in themselves for advancing towards energy efficient machining. If a carbon cap and trading permit scheme with a permit price of 15 €/tonne CO_2 was to be implemented for the general manufacturing industry, it would not significantly influence metal cutting companies to move towards more energy efficient machining, since its relative cost is small, even compared to electricity cost. Internalising external environmental cost as in the case exemplified here, does not appear to be an effective measure for reducing the environmental load of machining operations. This is because the cost of energy is small in relation to other cost components.

The conclusion must be that, in order to decrease the use of electrical energy of machining operations the internalised cost (here K_{CO2}) must be significantly higher than what is stipulated here. However, future cost and pricing trends can potentially change this. The carbon dioxide price in the EU ETS has fluctuated significantly over the last years, where it reached a top of 17 €/tonne CO_2 during 2011 but by the end of the year was below 10 €/tonne CO_2 (Bohnstedt et al., 2011). The cost of trading permits as used here in the calculations thus seems reasonable.

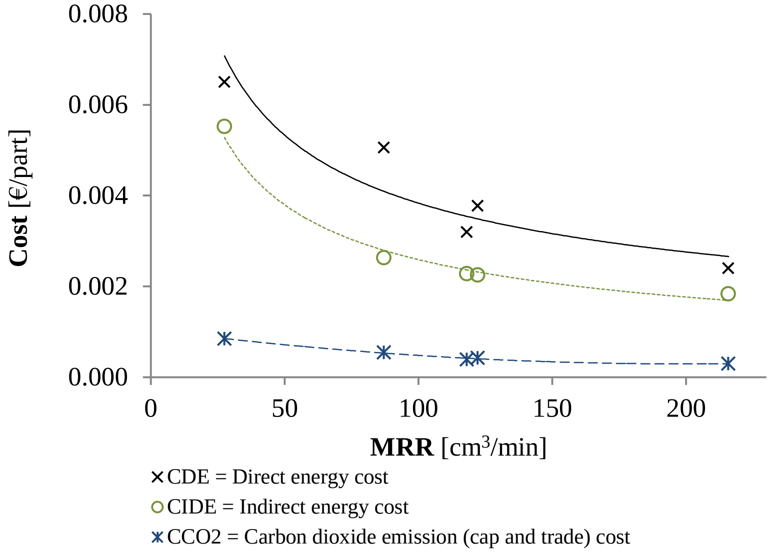


Figure 5.21 Relation between energy related costs.

5.3.6 Forecasting of cost components

Case E (Table 5.14) is used for further analysis of the energy cost in relation to the total machining cost, since it represents the optimal set-up in this study. Figure 5.22 presents the electrical energy cost for machining as the proportion to total machining cost for a present scenario and two future scenarios. The future scenarios presented are for the year 2016, where labour costs are linearly extrapolated from historical values (1995-2010) (Eurostat, 2008; Eurostat, 2012b), which gives a 13% increase by the year 2016 compared to 2010. The cost of electrical energy is less straight forward and not easy to extrapolate from historical data, since many parameters influence the results (economic situation, power supply grid, governmental energy policies, taxes and demand etc.). Hence two different scenarios are presented. First a scenario using linear extrapolation from recent historical (2007-2011) electricity costs (Bosch et al., 2009; Eurostat, 2012a) is presented, which gives an electricity price growth of 20% over five years. The second scenario is more extreme, where the cost of electrical energy has doubled over this five year period. Other machining costs are kept constant, e.g. tool cost and machine cost.

The level of automation is also altered for the three scenarios to capture the potential of the industry for increased automation levels as well as different situations in the industry regarding the level of automation. The one extreme case here is for complete automation during machining; thus no operator is dedicated for supervision, loading/unloading etc., which is similar to many applications of FMSs with CNC machines. The other extreme case corresponds to having one dedicated operator for each CNC machine at all times, which is not an uncommon situation in today's industry and which was the baseline scenario in the analysis presented above.

Alternating the different cost levels in relation to the automation level is important in a process planning perspective, since the actual set-up of the manufacturing system and the individual machine can influence the overall relation to environmental performance. If electrical energy use contributes a larger part of the total cost, then it will be more interesting to reduce this cost through more optimal use of machining parameters or tool selection etc. As seen in Figure 5.22, the cost of electrical energy will only constitute a smaller part of the total machining cost unless a drastic price increase can be expected and highly automated machining processes are employed. Otherwise, other cost components will dominate the total cost.

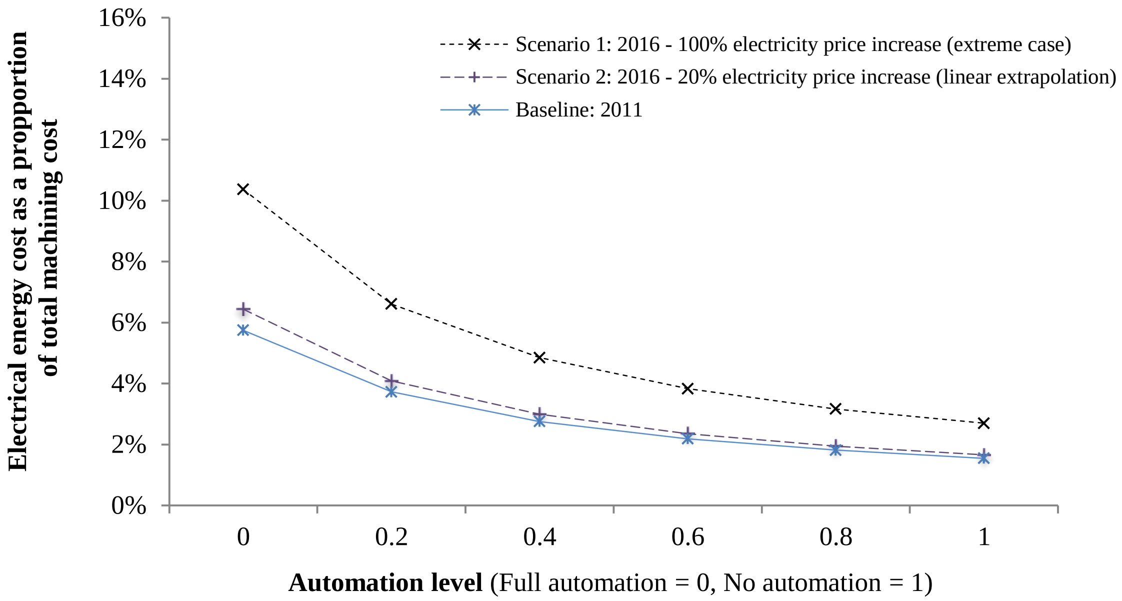


Figure 5.22 Possible future electrical energy cost trend in relation to total machining cost (including standby energy) for case E.

Machine tools with higher power output in combination with tools that can function under more severe machining conditions, will cause a shift of the optimal machining process window towards higher material removal rates and thus lower total energy consumption. Future tool advancement (e.g. geometries, materials, coatings) will consequently render the same tendency by repositioning the economically favourable process window due to higher permitted feed rates, cutting velocities and depth of cuts towards lower energy consumption (Figure 5.23). In theory, a state will be reached where machining can be performed under economically optimal as well as energy optimal conditions.

It is important to note that the exemplified part is simple and the total machining time is short, which means that, when MRR increases, set-up and idle times will proportionally stand for a larger part of the energy use and cost. With more complex parts that require longer machining times, idle and set-up times will contribute less to the total machining cost.

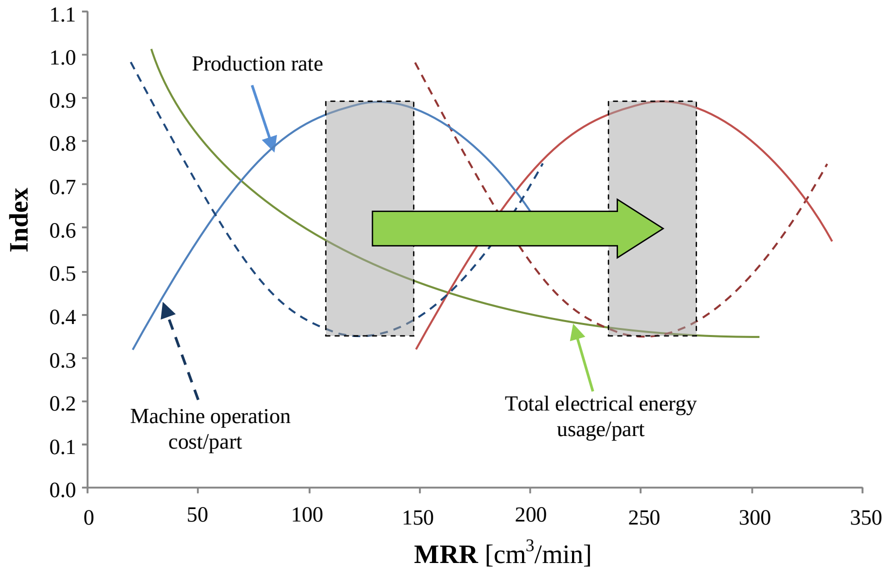


Figure 5.23 The advancement of cutting tool development in relation to energy efficiency and production cost and productivity.

5.3.7 Different machining factors' impact on specific energy

As mentioned in the introduction, specific energy is chosen as an indicator of environmental performance of machining operations. However, it can be confusing and difficult to relate various factors' influence on the total specific energy for a certain machining operation. Table 5.16 compiles values of the most important factors governing the magnitude of the total specific energy. The objective of the table is to create an overview of the ruling factors and their variation in contributing to the magnitude of the specific energy, which can be helpful when different options and strategies are being considered during process planning. It also aims at illustrating the complexity and the importance of having reliable data for the current machining set-up, since the resulting process can require a significantly higher energy use if some of the factors are overlooked, thus changing the calculations for optimal parameter and factors settings. As seen, only regarding the machine tool and neglecting the workpiece material can lead to erroneous decisions, since the specific energy needed to remove different types of materials can vary approximately by at least a factor of seven. Likewise, neglecting machining parameters' influence on specific energy can lead to poor process designs, from the perspectives of both cost and energy efficiency.

It is interesting to note that extremely high values of specific energies can be reached when machining at very low MRR. This is the case in micro machining (small feed rate and depths of cut) and machining of difficult materials, such as Inconel 718, which could generate 12-fold ratios between the highest and lowest machining parameter settings (as is illustrated in Figure 3.8).

The values in the table are based on published work, and the compilation should by no means be considered complete. However, the tendencies should be representative of the actual situation. The factor ratio describes the uncertainty and can be interpreted as a worst case scenario, which means that, if the factor is overlooked, its intrinsic effect can change by a multiple of e.g. two, three or seven. The factor ratio is calculated as the ratio between the largest and smallest value in each respective column, except for machining parameters, where it is calculated relative to each specific case. Each column describes typical values for each factor, where, for the workpiece material, states different materials, and, within each type of material, the typical specific energy values are stated, e.g. low alloy steels nominally range between 2.1 and 2.8 kJ/cm³. It is difficult to generalise the respective importance of each factor's influence on the total specific energy use for a specific operation, since it depends on the type of operation (micro machining, finishing, roughing etc.) where the machine tool in some of these cases stands for a proportionally large part.

From the above, the conclusion can be drawn that, in order to make effective decisions during process planning, accurate data are important. Faulty decisions are otherwise likely. However, it is often difficult to obtain all data, especially a priori data and data for a specific machining set-up.

In brief, the results using the model, experimental machining data and European Union's averages of different cost components indicate that not entirely new methods need to be employed and developed in an energy efficiency perspective, since the environmental benefits follow the economical machining curve to a great extent.

Table 5.16 Factors and their relative importance for energy use (values are based on handbooks, scientific papers etc. and formatted to fit the unit kJ/cm3).

Factor **Specific energy**	Machine tool[12]	Workpiece material	Machining parameters	Cutting tool	Auxiliary equipment
Factor ratio [max/min of nominal values]	~7	~7	~3	~2	~10
Observed typical nominal values	0.74- 5.45 [kJ/cm³] (fixed power mill) (Kara and Li, 2011) 1.16-1.77 [kJ/cm³] (fixed power lathe) (Kara and Li, 2011)	2.1- 2.8 [kJ/cm³] (low alloy steel) (Wiiburg-Bonde, 2000) 1.1- 1.8 [kJ/cm³] (cast iron) (Wiiburg-Bonde, 2000) 2.3- 3.0 [kJ/cm³] (stainless steel) (Wiiburg-Bonde, 2000) 3.0- 3.7[kJ/cm³] (heat res. alloys) (Wiiburg-Bonde, 2000) 0.5- 1.0 [kJ/cm³] (Aluminium) (Wiiburg-Bonde, 2000)	1.5- 4.0 [kJ/cm³] (SS 1450) (Wiiburg-Bonde, 2000) 1.9- 4.8 [kJ/cm³] (SS 2244) (Wiiburg-Bonde, 2000) 1.8- 3.2 [kJ/cm³] (SS 1550) (Wiiburg-Bonde, 2000) 0.8- 2.2 [kJ/cm³] (AISI P-20 tool steel) (Aggarwal et al., 2008)	4.8- 7.3 [kJ/cm³] (diff. rake angles) (Trent and Wright, 2000) 20.8- 23.3 [kJ/cm³] (micro milling) (Diaz et al., 2011)	1-10 [kJ/cm³] (5.6-9.5 [kW] sum aux. syst.) (Heidenhain, 2010)

[12] In theory the specific energy during machine standby is infinite, since MRR=0. These values are based on typical machining MRRs.

6 Synthesis and discussion

The overall scope of this chapter is how to achieve process planning performance improvements, the possibilities, prerequisites and strategies. The main part of the chapter focuses on improvement strategies and the chapter concludes with a discussion of research methods employed and the extent to which results are conditional on methods employed.

Process planning improvements can basically be achieved on two different levels in the company – on a structural level and the individual process planner's level. To this is added that improvements can be given in two dimensions in the form of technical and methodological aids. Since all organisations have their own respective process planning maturity level and context in which they act, no generic solutions can be given here. However, there are a number of areas that are important from a performance perspective and that need due attention. There are a number of common features between the organisations studied, which makes it worthwhile to address these areas in the advancement towards better process planning performance. Depending on the type of shortcomings in the specific organisation, different actions must be taken to manage process planning improvements. The surveys presented as part of this thesis focused on understanding industrial practice. As stated in the above, there are several deficiencies regarding these aspects, e.g. limited automation of process planning work, information management and performance measurement and low level of digitalisation in many companies.

The time perspective of improvements must also be regarded when planning for process planning improvements, where there are actions that require few resources and are easy to implement, the so called "low-hanging fruit". In contrast, some improvements must be assessed and evaluated over a period of time and undergo investment assessments etc. prior to implementation, hence calling for a longer time perspective. Altogether it is important to develop strategies and plan for how process planning should evolve in the current organisation. The following section will address some of the key areas of what a strategy for process planning should include.

6.1 Process planning improvement strategy

Short term actions will not be sufficient to be able to maintain competiveness on an ever changing market and environment in which the companies act; continuous and proactive improvements are needed. In this light it is important to have a strategy for the development of process planning for the future, where e.g. upcoming requirements from design, legislative and customer perspectives and their respective influences on process planning are included. This strategy should address the following:

- Performance indicators (present and future) - section 6.1.1;
- Methodological process planning aids – section 6.1.2;
- Technical process planning aids - section 6.1.3;
- Interface issues (internal/external) - section 6.1.3;
- Knowledge level (educational activities) - section 6.1.4.

To this is added the inclusion of production strategies and their relation to the process planning strategy, including aspects of:

- Total production cost;
- Automation levels;
- Process capability - section 6.1.5;
- Environmental impacts of machining - section 6.1.5.

A possible process planning improvement strategy can be based on the Six Sigma DMAIC methodology, where a continuous development process is initiated by defining objectives and setting performance indicators for these objectives accordingly. These are thereafter monitored and measured so that quantified performance information can be analysed from an improvement perspective so that the most effective improvement can be identified and implemented. It is then controlled so that improvements are sustained and render the correct results. The DMAIC cycle is repeated and an evaluation is made as to whether additional performance indicators are needed (see Figure 6.1). The improvement strategies and methods for gaining performance information are further discussed below.

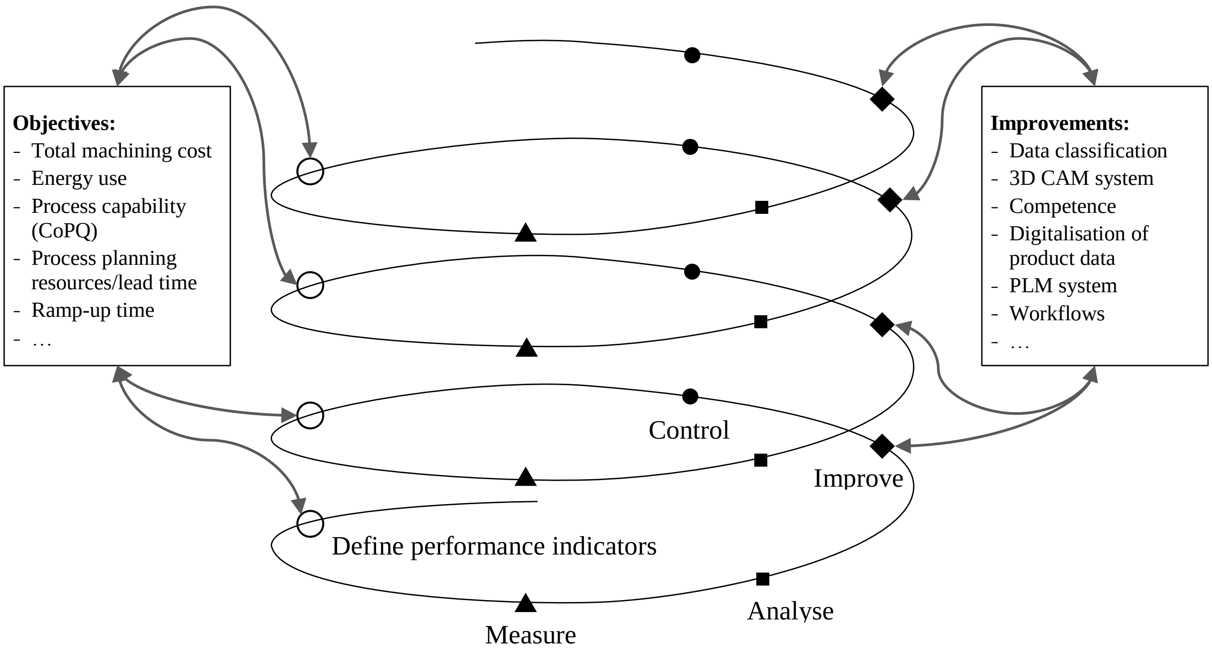


Figure 6.1 Process planning improvement strategy based on DMAIC methodology.

6.1.1 Performance indicators and performance measurements

There is an inherent problem in making process planning improvements when the company's knowledge about the process planning function is limited, as is indicated in the presented surveys, since the expected success due to improvements and investments cannot be systematically and quantitatively evaluated. In this perspective it is important to have knowledge about resource use for generating a process plan, so that investments in computer aids have a reasonable pay-back time, which means that investments should be motivated either from a process planning efficiency or effectiveness perspective, meaning either a reduction of planning resources or a better production outcome. If investments and developments in process planning cannot be economically justified, it will be difficult to defend extra spending. However, pay-back time cannot be set too short if it is a strategic investment – and what the alternative of not acting will result in must be evaluated.

A company that possesses substantial knowledge about performance 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 for assessing investments and therefore must act more on gut feeling and "guestimations" which can prove to be risky. Indeed, all investments are based on some risk taking, but the investor should be able to assess risks so that sound judgements can be made. There is thus a need for performance indicators and measurements.

A principal difference between process planning efficiency and effectiveness has been held throughout the thesis. It is of course essential to ensure process planning effectiveness in order to produce goods that fulfil the basic requirements of the customers. This comprises quality, delivery times and cost and is usually identifiable directly by the customer, but it also includes process capability and energy use, which are not directly perceived by the customer. Process planning efficiency, is in common with the latter, mostly difficult to recognise by the customer but will be seen indirectly in e.g. product realisation times, i.e. time to market.

The results of surveys conducted showed a need for implementing performance measurements. The exact scope and design of such a system depends of the individual organisation. Nonetheless, a few important aspects are worth mentioning.

First, it is a complex task to design performance indicators and collect performance data. Performance indicators should be used to set precise objectives in order to develop the process it measures. It is thus utterly important that designed performance indicators actually indicate desired aspects of performance; the risk of sub-optimisations is otherwise imminent. Focusing only on process planning resources, times and costs, singularly optimising the process planning function from this point of view and streamlining all tasks, will most likely in the end lead to machining processes with substandard performance. In short - the production aspect must be included as well.

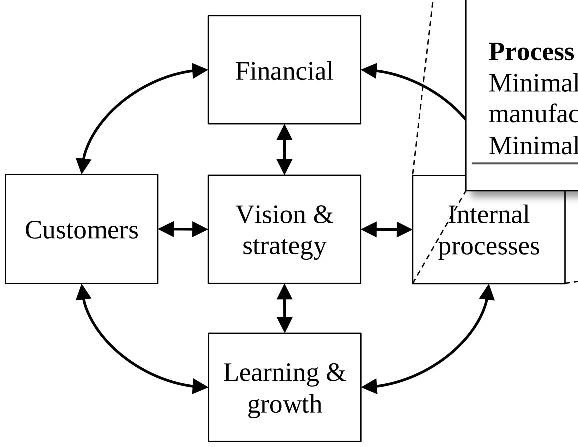
Second, performance measurements can prove to be a difficult task in themselves. Data collection must be resource efficient and preferably automatic (from CNC machines, probes, CMMs), and it should be possible for the data to be logged automatically in IT systems that are employed. This in turn demands a common plant network, where all subsystems are online (including machines), and this is not always the case in industry. In addition a data management system is required, and as shown, this is not very common in the industry where only 2% of the companies that responded in survey 4 have a PLM system and 19% in survey 1 have a PDM/PLM system.

Third, the use of performance measurements must be established and accepted in the organisation. It is consequently a managerial issue to establish acceptance, which in turn is dependent on the organisational culture, organisational psychology aspects and, on a larger scale, industrial policies, where it has long time not been accepted to measure performance of individuals. These are accordingly necessary to address prior to changing established aims and goals.

In the work to define effective performance indicators it is important from a managerial perspective to identify what is value adding and non-value adding for customers in relation to process planning work. This could be followed by making value flow analyses to better understand value creation and where improvements will give optimal results.

Performance indicators of process planning effectiveness are necessary and may incorporate production cost, lead times, unplanned stops and process capability as well as energy use in the form of the specific energy demands of machining. Process capability can be used as a performance indicator of machining, where C_p/C_{pk} can be one indicator and a certain C_p/C_{pk} value can be used as a metric. This of course implies that a certain quantity of the products or processes must be measured. Most companies measure to some extent but the values are not always saved, thus follow-ups or calculations of PCIs are hampered. Another aspect of using PCIs as performance indicators is that they can also be used as classification criteria for existing operations and, as such, be used as an aid for operation reuse, where the consequence is that high performing operations can be employed at the same time as the selection is facilitated. Thus effects are dual – both effective and efficient.

To introduce performance measurements in novel environments, it is better to start on a limited scale with the most basic performance indicators wherefrom they are developed. When initialising a measurement scheme, both process planning efficiency and effectiveness should be captured. A performance measurement scheme can be presented in the form of a balanced scorecard for the internal processes. Figure 6.2 give a suggestion of such a scheme, where some of the fundamental indicators of process planning performance are included. A reasonable starting point to indicate process planning efficiency would be to measure the process planning resources used (man-hours and lead times). It is wise to use both man-hours and lead time, since any discrepancy between the two signals constraints and waiting times in the work flow (e.g. decision making time beyond process planners' control) should be followed up. Process planning effectiveness in terms of machining process performance should include at least one quality aspect of the finished products, the capability of the process, time before a robust process is achieved. It may also include some process rate indicator and utilisation level of the machine(s) employed. Depending on the current product, metrics can be redefined to reflect reasonable metrics for the current situation. This is particularly relevant for lead times, which are highly dependent on the type of product being planned.



Internal processes – example CNC machining

Objective	Indicator	Metric
Machining process		
Product quality	C_p/C_{pk}	X
Maximal process rates	Lead time	X min
Robust processes	C_p/C_{pk} (intrinsic)	X
Short ramp up time	Time to nominal C_p/C_{pk}	X h
Maximal utilisation level	Downtime	X%
Process planning		
Minimal time to manufacturing	Planning lead time	X h
Minimal resource use	Planning man-hours	X h

Figure 6.2 Balanced scorecard approach for process planning performance.

In essence, the organisations should capture the performance objectives of the company and transform them into process performance indicators. However, it should also be mentioned that initiating measurements on a small scale is better than not measuring anything. Having some performance indicator in place, despite not being able to capture all aspect of process planning performance, is better than nothing at all. Over time these indicators can be developed to better describe performance. It is not likely that a performance indicator is perfected at once. It is therefore important to initiate a culture of employing performance measurements for assessing performance, rather than relying on assumptions.

It is also important to note that, although process planners are important, they do not act independently of their environment. There is always an organisation involved, with managers, production engineers, machine operators and fellow process planners. In production where operators load/unload, perform in-process control etc., the work of the process planner is not the only parameter that influences the outcome. If a blank is not correctly clamped in the machine, gauge values are misinterpreted or tool changes are neglected, the performance will be poor, irrespective of the process plan and the NC program's quality. Altogether, production in general and CNC machining in particular, as focused on here, are a joint effort made by the whole organisation, where each part plays its vital part. Process planning lead times may be influenced for example by decision making time by managers and information processing performed somewhere else etc. Accordingly, some problems must be resolved by considering the whole production realisation flow in order to resolve bottlenecks, if the root of the problems resides somewhere else.

6.1.2 Methodological process planning aids

The approach of using process capability as operation selection criteria can be viable when new operations are designed, since existing operations' capability levels can be extracted and the criteria of new processes can more effectively be targeted (section 5.2.4). Another benefit is that deficient processes are easily identified and improvements can be made where needed. Process plan revisions are one way to improve established machining processes to ensure that the best available technology (e.g. tools and machining parameters) is used. As indicated by the interviewed companies in survey 2 (but not included in the research), revisions of existing machining processes are primarily only made when customers demand lower costs or when tool vendors give suggestions for improvements. However, it is preferable for revisions to be initialised by the individual company in a systematic way, where an effective method can be based on the C_{pk} level of the operation.

A few requirements must be fulfilled for enabling classification of operations based on process capability:

- Data must be systematically measured and saved;
- The intrinsic capability should be measured;

- Data should be easily retrievable and transparent.

It is essential however if more process planning data are being managed, that this is done in the most efficient way. This problem was highlighted in Survey 1, which indicated improvement needs in information management, since much process planning time was dedicated to information reconstruction, which is typically non-value adding work. Another aspect of information and data management that is important for overall process planning performance but which has not been included in this work is requirements management. To improve performance, it is vital to understand how requirements are presented to the process planner and how output is influenced. A possible solution is the implementation of some PLM system or better working methodologies and routines for information management (storage and retrieval).

6.1.3 Technical process planning aids and internal and external interface

The highest and, in an automation perspective, ideal state of process planning can be considered the fully automatic level, where a product data model is the input and a complete and optimal process plan is the output generated without any human intervention. As described in three surveys, the present industrial situation is far from this scenario. However, natural questions are whether this level is ever possible to reach and, if yes, what the time horizon would be to reach it.

These questions are important since two principal improvement routes appear: the first complete automation of process planning and the second development of human centred semi-automated process planning.

It is a managerial task to define what measures are appropriate to take in order to develop process planning for the future, where increased demands on cost efficiency, flexibility, product quality and environmental performance can be expected. For the general sub-contractor, where demand and product flexibility are high, the fully automated state appears distant. For companies with rather defined products, input and customers, but with high complexity, the fully automated stage also appears distant, since their competitiveness is often defined by their skill in innovative machining solutions and ensuring high quality products etc. A fully automated CAPP system, where it principally is a matter of interpolations rather than extrapolations, would not benefit innovation in metal cutting. The industry branch where full automation appears most likely is where companies work closely with regular customers (to ensure homogenous input), product complexity is low, machining lead times play a secondary part and demands for innovation and introduction of new technology are limited.

Automated process planning systems also require reliable and up to date data in order to produce effective process plans. This is a part that cannot be neglected and an effective data classification system is required here as well.

In the strategy plan for process planning, the company should state a desired level of automation regarding process planning work, which must be reasonable considering the organisation's current position. Figure 6.3 shows one such strategy for human process planning based on a suggestion for how commercially available computer aids can support process planning. Computer aids are here primarily focused on non-value adding activities. A similar process flow could be developed for the individual company where functionality and prerequisites of commercial software are mapped. Software investments are in reality more complex than this, where interface aspects must be taken into account as well as other financial aspects and strategic considerations, which include system support, maintenance, longevity, vendor dependency etc. Digitalisation is one case which is not entirely a process planning issue; due to customer/supplier relations, formats, procedures and methods must be agreed upon.

As discussed above, the fully automatic process planning function appears remote, which means that process planning will revolve around human beings for some time still. It is thus essential to design process planning so that it is as efficient and effective as possible for humans. To enhance the performance of process planners, i.e. to enable the process planner to spend as much time as possible on value adding activities, such as effective decision making, process planning aids must be implemented where maximum effectiveness is achieved.

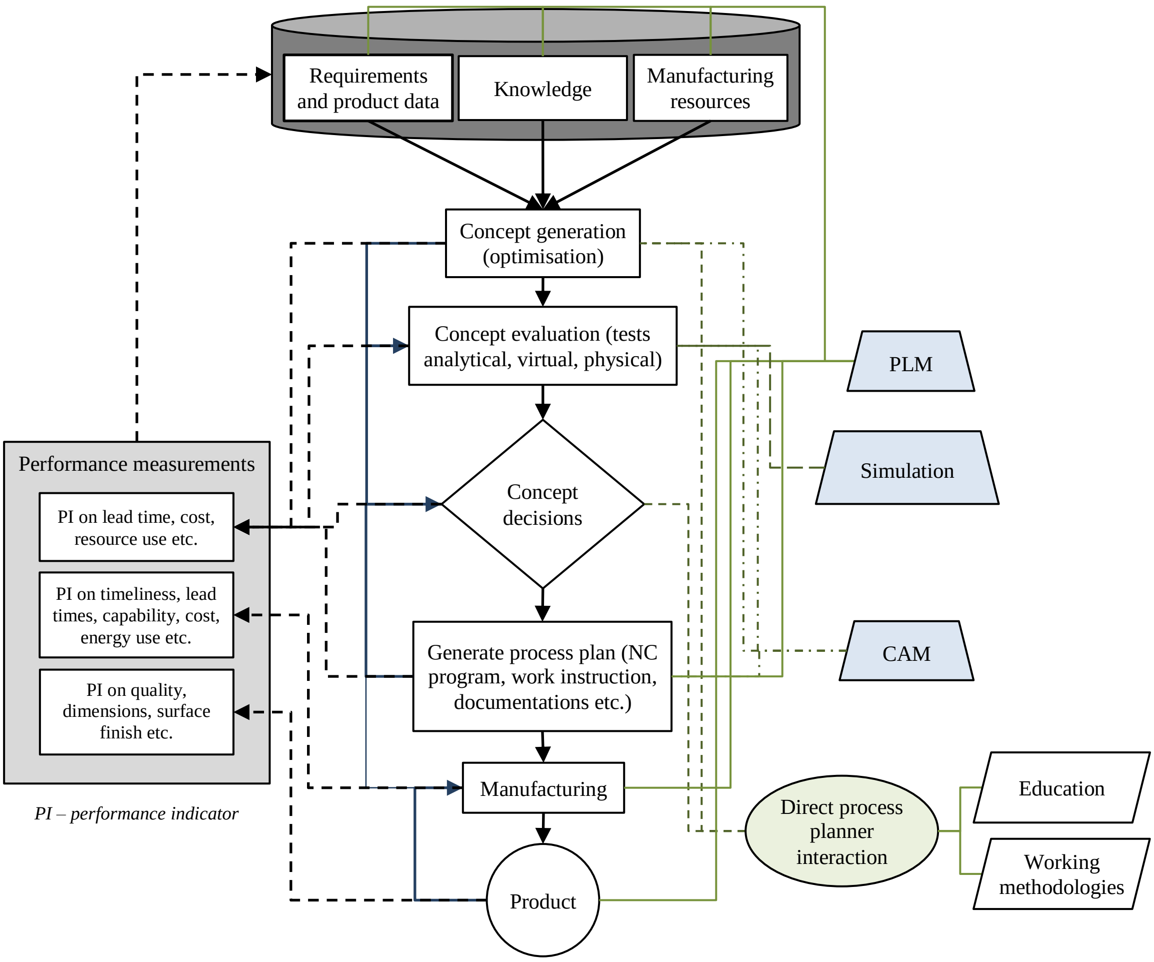


Figure 6.3 Revised version of Figure 2.3, where possible process planning aids are included for performance improvements.

Our society and industry are becoming more based on digital information; thus software interface issues and data transfer must be managed. While this is important internally in the enterprise, the external interface between customer and suppliers cannot be neglected. File format compatibility is important throughout the supply chain to reduce overall product realisation times. This is an aspect to consider when making software investments. As identified in section 5.1.4, three levels of companies can be identified based on digital product data usage. Firstly are the companies that have no 3D CAD product data. Secondly, companies that uses both digital and no 3D CAD data and thirdly companies with primarily 3D CAD data. Each of these levels has different prerequisites for how process planning computer aids can be used, and this is an area where further research is needed to enhance the understanding of what type and what effective design of computer aids would be. Related to this is the question of whether a continuous development or a technology leap approach would be more effective.

Many PLM systems enable integration between companies, where suppliers can extract data from the customers and work on the same product models etc. However, it presupposes that the bulk of information is digitally available (as e.g. 3D CAD models). The ambition of the STEP-NC concept is promising, but the time horizon for its implementation in industry is uncertain and depends on more than the technical level of maturity of the concept. As has been noted several times in this thesis, despite a history of more than 40 years with CAD/CAM, its industrial implementation is still far from being completed. To this is added that STEP-NC has even more ambitious aims, since its ultimate one is to create seamless integration throughout the whole product realisation chain – including the machine tool by replacing NC code (ISO 6983 G-code). This means that traditional process planning methods will remain for a long time to come.

One method for implementing computer aids is to start with reoccurring products or simple products, develop process planning methodologies for those and migrate them to the other products and processes. To do so, it is vital to have quantifiable objectives, based on performance indicators for process planning and CNC machining as a starting point, so that all changes and developments made can be quantified, as was proposed in the DMAIC model above (Figure 6.1). For companies with a wide variety of input to process planning, computer aids must be flexible regarding input (file formats and solid modelling techniques) and automation levels (different levels of human interaction). Initially, this can be achieved if the process planner is supported in the planning activities, so that administrative, clerical work and information retrieval etc. are supported by computers. Implementation of such process planning automation approach should be gradual, so that databases that are needed can be developed over time and thereby continually decrease the need for human interaction so that process planning can be adapted to the current prerequisites and at the same time be efficient.

For a manufacturer of high cost products as many aerospace manufacturers are, it is often easier to economically motivate investments in process planning aids. A machining error here that leads to discarding the component may entail a cost of up to a million SEK, in product cost alone, which implies that avoiding the occurrence of one error can roughly carry the whole investment cost in these more extreme cases. This can be illustrated in analogy to Figure 3.2, where *investment cost* can replace *explorative process planning cost* in the graph. The investment cost must be lower than the reduction in machining process planning time and cost over a defined time period. Support and maintenance of computer aids must however also be included in the investment cost, since some of the systems require substantial resources to operate. Parameters that influence the return on investments in process planning aids are, e.g. company size, number of process planners, number of produced process plans (novel, recurring and revisions), production batch size, product cost, CoPQ and product complexity etc.

6.1.4 Knowledge level

The introduction of new and more complex computer aids is not only a matter of technical and managerial decisions that must be made. It also changes the knowledge requirements for process planners, which in turn need due actions and considerations, not least because a change in desired knowledge may lead to a substantial amount of process planners in the current organisation lacking the new knowledge requirements and, as a consequence of that, oppose implementation of new technology. Any change in technology must therefore be preceded and supported by educational activities.

It is vital to secure the knowledge in the organization, when more and more of the company's value is based on intangible assets such as the knowledge of its employees. The knowledge level of process planners has not been studied or evaluated empirically in this work. However, survey 4 highlighted a number of process planning problems in the industry related to competence and information management problems. Despite this, a number of important areas should be addressed when process planning is discussed, due to its importance in process planning efficiency and effectiveness.

It is also critical to define upcoming competence requirements and thus educational activities or recruitments. The need for this stems from implementation of new manufacturing technology (machines, tools, materials etc.), software, theoretical and analytical aspects of metal cutting, how environmental requirements influence machining etc. It is also vital to identify the need for and existing methodological knowledge in the organisation.

Methodological knowledge refers to the ability to understand and perform procedural aspects of process planning, e.g. how various activities and factors influence performance in relation to the act of planning, where data are retrieved most efficiently and how to gain new knowledge etc. This is an important area with respect to the continuous development of the process planning function.

Technical knowledge refers to the act of designing a machining process that is technically optimised with respect to tooling, machining parameters, tool paths etc. The term process planners' experience typically encapsulates this type of knowledge. One problem with experience is that it commonly only implies a rule based type of knowledge, i.e. how things are to be done but not why things are done. A consequence of this is that process planners often are dependent on tool vendors' tooling recommendations and/or use experience based tooling and machining parameters. To advance process planning, it is vital to enhance analytical knowledge.

A higher level of technical competence regarding metal cutting would contribute to better machining processes and output, and thus higher effectiveness. The efficiency of process planning would likely increase as well, since the likelihood for generating an error free and optimal process plan the first time increases. Hence the need for iterations decreases with more technically knowledgeable process planners.

6.1.5 Production objectives

The strategy concerning development of the production system is a management decision and as such not part of this thesis. It nonetheless influences the act of process planning. Aspects of machining should be addressed as part of developing production both process capability and environmental aspects of machining. Strategies for enhancing process capability have been discussed extensively above, so strategies for this on the process planning level will be omitted here. However, strategies for improving environmental performance can be regarded from a short and long term perspective, where the former directly relates to process planning work. The latter on the other hand mainly relates to research and development in academia and industry (cutting tool and machine tool manufacturers etc.) (see Table 6.1).

In order for the industry and the individual company to advance towards more environmentally friendly production, a green machining strategy could be developed, where mainly the short term aspects of Table 6.1 are assessed by building the organisational knowledge around these areas. Working with these aspects is more like picking the "low-hanging fruit" but, as shown in various models and experiments here, the achievements can be considerable; hence these efforts should not be overlooked. Since the use of advanced process planning technology is limited in industry, there is a need for a development of guidelines, best practices, rules and easily used analytical tools etc. to assess green machining in daily process planning work. The company could start by defining the specific cutting energy profiles for the most commonly machined materials and apply a general approach of optimising machining parameters for high MRR.

Table 6.1 Short and long term aspects of green machining.

Short term	Long term
Knowledge about specific cutting energy	Tool development (materials and geometries)
Material properties database	Cooling techniques
Cooling techniques	Machining dynamics
	Machine tool development

Being able to optimise the machining process in relation to all production objectives is an intricate task, which has been highlighted many times in this thesis. Figure 6.4 illustrates the complexity of the process planning problem, where the dimensions of machining outcome included in this thesis are set in relation to process planning decisions and the interdependence between different dimensions of outcomes. Some of these aspects are easier than others to estimate analytically, whereas other aspects require posteriori information. The figure also illustrates the complexity of process planning that when optimising operations for a certain dimension (criterion) also other dimensions are influenced.

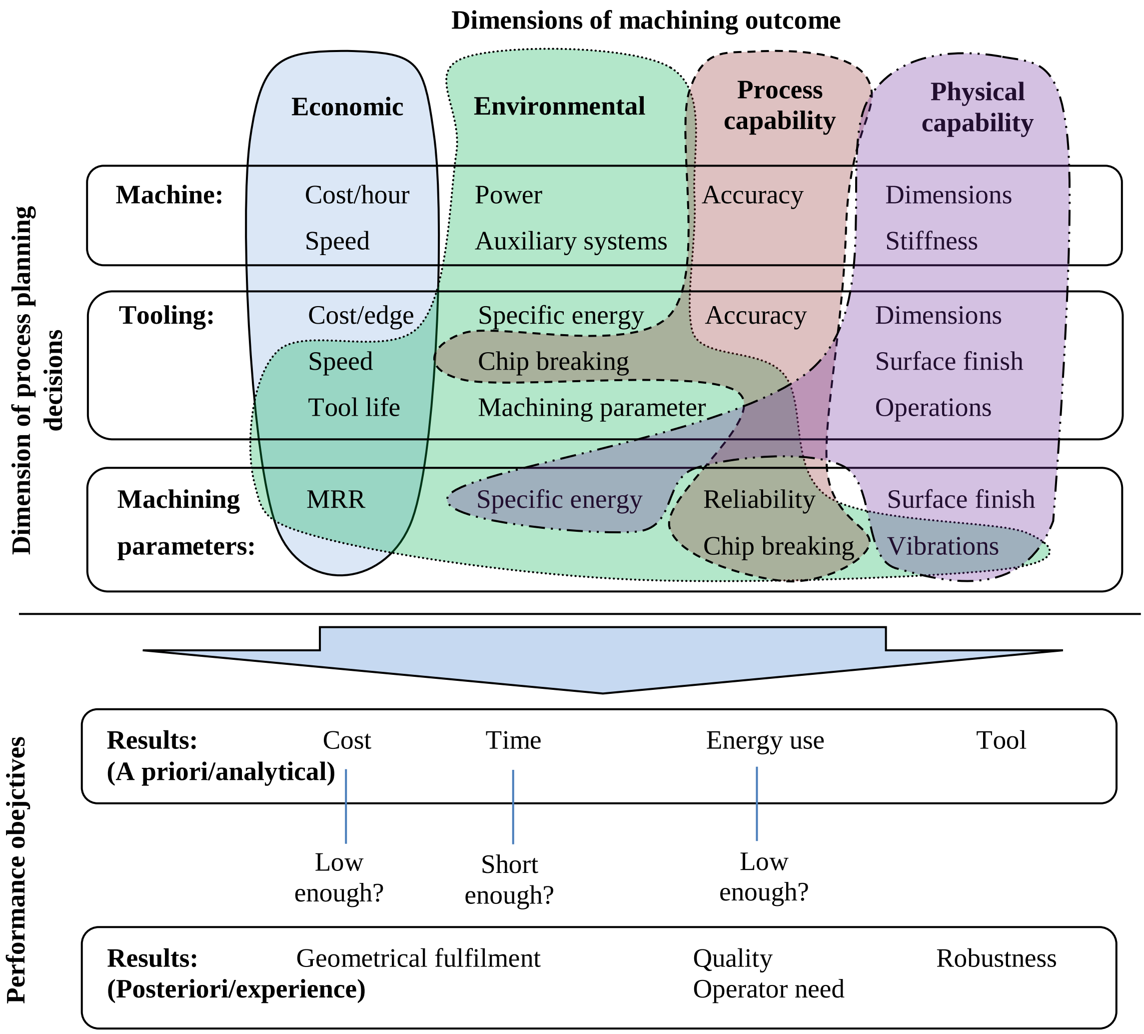


Figure 6.4 Relation between dimensions of process planning decisions and dimensions of machining outcome.

6.1.6 Summary of results in relation to research questions

The main findings of this thesis in relation to the stated research questions are compiled in Table 6.2. The overall research question "How can process planning for CNC machining with a focus on production performance be improved, and in which operations with and without prior knowledge are managed effectively?" was addressed in the above sections where improvements in process planning work should be based on an overall improvement strategy in the company, where production objectives as well as technological and methodological aids are included.

Table 6.2 Research questions and principal findings.

Research questions	**Principal findings**
1. What are the principal process planning deficiencies in the industry?	A lack of knowledge about process planning performance, information management problems, non-homogeneous product data exchange and that many companies have a low level of digitalisation are identified as deficiencies in industry.
2. What are the available process planning aids and to what extent are these used in the industry?	PDM/PLM systems have found limited use in industry and there is also a substantial proportion of companies that do not use 3D CAD data and 3D CAM software. Feature based CAM is also not widely used.
3. What are the possibilities for concurrently meeting stricter demands on low total machining cost and energy efficiency?	There are no inherent contradictions between cost and energy efficient machining, although they do not necessarily coincide. With the development of cutting tools, these factors will decrease discrepancies.
4. How can an improved process planning methodology decrease operator dependency in CNC machining through the design of more capable processes?	Through the use of process capability data as a basis for systematically selecting operations, more robust machining can be created. To decrease operator dependency the intrinsic process capability must be captured and used, where in-process controls are excluded.

6.2 Method and results discussion

Some of the ideas and results presented in this thesis are also applicable to other manufacturing processes than metal cutting. This is particularly the case for the general areas of performance measurements of process planning and use of process capability data during process planning to enhance the performance of production outcome.

The validity, generalisability and intersubjectivity of the results should be commented upon. Results of surveys of companies can always be questioned in terms of their validity for the industry at large, especially when small samples are used, as is particularly the case for qualitative studies. Putting survey sample size in relation to the total size of the industry can give an understanding of the generalisability of the research. It is difficult to estimate the total number of metal working companies that uses CNC machining, but a search for "CNC" and "bearbetning" (eng. machining) on www.industritorget.se, a web portal for Swedish subcontractors returned 769 hits in the year 2008. By the end of 2011, the same key words returned 1515 hits. Although, this is not all the companies in the sector in Sweden, it gives a hint of the sector's size.

The principal aim of the surveys was not to draw general conclusions about the whole industry but to better understand the process planning environment, requirements, methodologies and basics of process planning work. These studies depended on the perception of respondents and interviewees and thus special attention was paid to finding employees with knowledge representative for the research scope and, when possible, a team of employees was used instead. Despite these inherent problems of generalisability with the research methodology employed here, the general tendencies and conclusions drawn should be considered valid, which is discussed below. Care has also been exercised not to draw conclusions about the whole industry but merely to point out deficiencies and tendencies. Survey 4 had the aim of providing more general information about the industry at large. The results that were generated here pointed in the same direction as survey 1, which had overlapping scopes (mainly regarding the use of digital data in process planning). This strengthened the validity and generalisability of the results of survey 1, which had a smaller sample. The four-year time difference between the first and the last survey as well as the similarities in results point in the direction that the response was not random and dependent on the companies sampled.

In a report by Swedish Statistics (2012) on the Swedish manufacturing industry's use of IT, 28% of the companies (ten employees or more) use automatic exchange of product data and information, which is similar to other industry sectors in Sweden. This also points in the same direction as some of the results presented here and thus strengthens survey results - that digitalisation of data has not entirely penetrated the industry sector. In a survey of the machining business in the U.S. by the magazine Modern Machine Shop, it was found that 4% of 183 companies have implemented PLM and 67% had 3D CAD and/or use CAM (Korn, 2011). These figures are in line with the findings of the surveys presented in this thesis.

A different research method for identifying deficiencies in the industry would be to more closely study process planning work through time studies at companies. This approach would possibly result in more reliable and detailed information about the specific company's process planning efficiency and the ratio between value and non-value adding activities. In this way it would be possible to identify activities that need support and development. Such a research approach could be carried out by using existing logs of process planning software, shadowing techniques, conventional work sampling techniques or by using work sampling technology, as exemplified by Murgau (2009). However, doing so is difficult and requires acceptance by the organisation and employees in the companies, besides the time that is required to carry out such research. This is primarily an undertaking in the individual company so that constraints and bottlenecks in process planning can be identified.

The intersubjectivity of the survey research has been addressed in such a way as to avoid leading questions. In survey 1, a substantial ratio of questions was open-ended so that not only multiple choice questions were used. The survey was also tested prior to posting questionnaires. Three companies participated in tests where respondents were able to comment and discuss answers after filling out the form. In this step, a few questions were added and others were reformulated. In some cases, to make it easier to fill out the questionnaire, pre-defined multiple choice questions were used. However, as many as possible different alternatives were then provided to avoid leading the respondent.

To assess the validity and intersubjectivity of the experiments and data used in the work on energy and cost efficiency of machining, data and constants were selected to reflect a typically average company. These are attempted to reflect job shops or conventional subcontractors in the manufacturing sector. Many data were based on EU averages, and sensitivity analyses were performed and reflected upon through the use of different scenarios.

It is relevant to consider how further surveys of companies can generate more generic results so that conclusions can be drawn on the industry at large. Conducting interviews with a larger sample than has been presented here would be time consuming, and the results would possibly still be difficult to generalise. Studying process planning in an even more limited sample and performing more in depth studies and longitudinal time studies in a process planning improvement program would certainly provide interesting knowledge that could be used to develop an understanding of how changes in process planning methodology influence performance. In reality, it is difficult to start up these programs and be able to follow them in a longitudinal study, since research work as presented here has limited time frames. Results and the possibilities to conduct such research are dependent on company dedication. Following the implementation of new computer aids would also be interesting, but this is also difficult to coordinate with the time frames of a research project of this kind.

Surveys that use 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 be entirely attributed to limitations in research methodology, but also indicates problems and a lack of quantifiable information about their process planning in the surveyed companies.

It is worth discussing whether the findings in this thesis are typical for the Swedish manufacturing industry or are also valid on the global level. The results of the interview surveys reported here were carried out in three Swedish and three Australian companies and, although the sample is too small to draw any general conclusions, it did not suggest any radical difference in process planning work between these two countries. This is further supported by the results by the Modern Machine Shop's survey (Korn, 2011) (although it is not a scientific publication).

The research presented in this thesis has mainly considered an organisation with dedicated process planners. However, organisational approaches exist, where the machine operator and the process planner are one and the same. Hybrids also exist, where a process planner performs technical planning and operator performs geometric planning, mainly NC programming and verification. The use of operators as process planners 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 operators' work. This is an area in which further research should be conducted to gain greater knowledge in how to develop process planning aids for these groups. The methodological approach should be similar, however, to allow more time for value-adding activities.

Parameters for modelling and analysing costs and energy use in CNC machining were chosen to represent the average manufacturing company, which means that results will differ between organisations and circumstances. However, the results are in line with similar studies in the literature that are mentioned here. The work on energy and cost efficiency in CNC machining was done in 2009. Since then, other and similar work has been carried out by other authors. Due to a change in the research focus, no further development of this work was made thereafter. Other researchers work will therefore be briefly discussed and compared. Rajemi et al. (2010) had a similar cost model and experimental turning experiment, but the aim there was to optimise cutting velocity according to minimum energy use and machining cost. The results showed that optimising on cost and energy use (including embodied cutting tool energy) gave similar cutting velocities. However, if embodied tool energy was omitted, a higher cutting velocity was needed to optimise the operation. This tendency was also indicated in the results presented in this thesis, albeit not as poignantly. This is probably because Rajemi et al.(2010) only varied the cutting velocity, the influence of which on specific cutting energy is not as radical as the influence of feed rate. In a sequel to the former study, Mativenga and Rajemi (2011) used a different optimisation method where feed rate, depth of cut and cutting velocity were all altered, and found that optimisation for minimum cost and energy coincided. Findings by Mori et al. (2011) showed a reduction in machining energy consumption with an increase in MRR milling and drilling operations. This indicates that findings on improvements in energy and cost efficiency in turning are transferrable to other machining processes as well. Pusavec et al. (2010) demonstrated that the use of cryogenic cooling results in the most cost and energy efficient machining solution compared to high pressure jet-assisted machining and conventional cooling fluids. This was a consequence of being able to use higher cutting velocities (higher MRR). Branker et al. (2011) developed a cost model based on the model presented in this thesis but that contained more details on carbon emission aspects. The model was used to evaluate total machining cost in relation to carbon emissions with the geographical location of production.

The discussion above and the conclusion given in the next section are based on the empirical findings of this thesis. Exceptions may, and possibly do exist, that have not been indicated or captured in this work. This is the delight of empirical research - that no absolute laws can be created from empirical investigations, where Karl Popper's "black swan problem" is always present to some extent.

7 Conclusions

The chapter presents findings and highlights a number of specific conclusions and results of this thesis. Areas that need further research are also identified.

The general aim of this thesis was to depict the importance of process planning for creating value for the manufacturing organisation by specifying its relation to key competitive factors and performance indicators. Research in process planning has principally addressed technical issues, such as selection of tools, machining parameters, use of computer aids for process planning automation or information exchange etc. The holistic and methodological perspective of process planning has to a much lesser extent been researched, where the aim of this thesis was to synthesise the multidisciplinary nature of process planning from a performance perspective and highlight some of the more important aspects.

The principal approach that has been proposed throughout this work to increase process planning performance is through the use of human centred process planning. Aids should be given and designed so that maximum process planning resources are spent on value adding activities. The empirical research was carried out in surveys, case studies and experiments. The main findings and conclusions are stated hereunder.

Introducing performance measurements in process planning is vital for verifying and quantifying performance in industry. This is a necessary action for being able to identify deficiencies in process planning and verify that actions taken to improve process planning render the desired effects. Limited industrial use of performance indicators of process planning was one of the main findings in the surveys that were conducted. Other important findings of the surveys are:

- Information management problems imply that resources are used for non-value adding activities such as information reconstruction;
- There is little use of advanced process planning technology in relation to what is commercially available;
- There is a low level of digitalisation of process planning information in a substantial part of the industry.

A systematic approach for managing production runtime data based on process capability indices to aid process planning has been presented. This has the potential to increase the effectiveness of process planning by focusing on robust processes and minimising CoPQ. A method was presented for calculating CoPQ based on C_p/C_{pk}, which can be used to evaluate the relation between CoPQ and appraisal activities (in-process controls). Classifying production runtime data from specific operations as PCIs and using this information during process planning potentially results in higher process planning efficiency since knowledge is managed more purposefully and the selection of operations is facilitated. Process capability was analysed from an automation level perspective, and the importance of the intrinsic process capability was emphasised for advancing towards higher levels of automation without in-process controls (manual or automatic).

No inherent contradiction between total cost and energy efficiency in CNC machining could be found using an analytical cost model and experiments. These findings influence the way machine tool use is regarded, since better utilisation of available resources implies more energy and cost efficient machining operations as well. The cost of electrical energy in itself does not influence the advancement towards making energy savings during CNC machining, since its cost is small in relation to other machining costs. The exact relation and the optimal selection of machining parameters depend on a number of factors, such as the machine, tooling and workpiece material, where accurate data are important. Research aiming at developing technology (e.g. cutting tools) and methodology for higher material removal rates per energy unit is important from a cost and productivity perspective as well as from an environmental perspective. In general, aims to increase MRR through cutting tool and machining parameter selection are beneficial from an energy savings perspective.

This research has contributed to an increased understanding of process planning and the perspective of automation strategies for process planning activities. Future challenges in the production organisation have been addressed in relation to process planning, where mainly high process capability and energy efficiency were analysed. It has also been maintained throughout this thesis that process planning performance is not independent from its environment, which means that it is necessary to consider internal and external interfaces in the companies when making changes. A focus on systematic process planning and level of digitalisation could not be correlated to any prerequisites of the companies. This indicates that it may be persons in the organisations or customer/supplier relations that are ruling rather than the investigated factors.

The work has also highlighted a discrepancy between industrial needs and research foci. To enhance the industrial process planning performance level, resources should be focused on developing methodologies, easily used, effective, cost efficient aids and efficient methods for implementation. This is particularly important for SMEs, which have more limited resources for making investments and maintaining advanced computer systems than larger enterprises. It is also central to regard the current level of digitalisation of the company and the underlying factors to be able to successfully implement computer aids for process planning to enhance the level of automation.

Although the research on industrial organisations was carried out primarily in the Swedish industry, it is reasonable to assume that the findings and conclusions are not limited to Sweden alone.

7.1 Future work

A few areas for future research have been identified based on the findings of this thesis. Future work should be directed towards developing process planning methodologies and strategies in an industrial organisation, where effects on performance can be studied longitudinally.

Implementing green machining strategies and guidelines for the industry that can be used in daily process planning work is also interesting. It is important that they can be studied over a longer time period to verify effects on energy use and carbon dioxide emissions as well as impacts on production costs. Here more research should be invested in clarifying the embodied cutting tool energy for different tool materials in relation to total machining cost.

More research should be concentrated on understanding and developing performance measurement systems for process planning. Here the pros and cons of a continuous approach versus an audit approach should be addressed. This work should particularly focus on how to connect production outcome to process planning work, which is potentially challenging.

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Part IV
Appendices

8 Appendices

Appendix A

Table 8.1 Survey 1: Characteristics of respondents in survey presented in section 5.1.1.

Process planning specific questions

Concurrent engineering	No integration between activities	Some integration between activities	High integration between activities	Blank answers	
	26%	17%	26%	31%	
Percentage of design demands vs production demands	A: 0-25%	B: 26-50%	C: 51-75%	D: 76-100%	
	50%	12%	19%	19%	
Priority of demands put on the preparation	High priority	Average priority	Low priority	Blank	
Logistic flow demands	10%	45%	40%	5%	
Production lead time demands	45%	43%	7%	5%	
Tact time demands	40%	48%	7%	5%	
Quality demands	83%	10%	2%	5%	
Limited personnel resource demands	33%	52%	10%	5%	
Percentage of products virtually verified in 3D for collision avoidance	A: 0-25%	B: 26-50%	C: 51-75%	D: 76-100%	
	59%	24%	5%	12%	
Ruling alternatives for CAM software selection	A: User friendliness	B: Compatibility with CAD software	C: Compatibility with other software	D: Price	
	37%	22%	17%	12%	
Does a general process planning methodology exist?	Yes, within company	Yes, within company group	No		
	55%	5%	40%		
To what extent is planning methodology obeyed?	A: 0-25%	B: 26-50%	C: 51-75%	D: 76-100%	Blank
	0%	14%	19%	24%	43%
What are the main pros of your coordination software?	Coordination	Overview	Decision control	Verification	Other
	25%	88%	25%	63%	
What are the main cons of your coordination software?	Inflexible	Not suited for company needs	Cost	Administration	Other
	63%	13%	25%	25%	

Are there parts of process planning that are more problematic and recurring?	Yes	No	Blank		
	33%	57%	10%		
Is there a product coordinator?	Yes	No	Blank		
	45%	55%	5%		
Is the process planning role separated from metal cutting engineering role?	Yes	No			
	26%	74%			
Is the metal cutting engineering role and method development role separated?	Yes	No			
	19%	81%			
What are the principal means of communication during process planning?	Telephone	E-mail	Personal contact	Through coordination system	Other
	45%	60%	57%	7%	0%
Are follow-ups conducted to monitor problems?	Yes	No			
	62%	38%			
How is process planning documented?	A: Evaluation form	B: Process planning data is filed	C: A report is prepared	D: Computer generated report	E: not at all
	7%	48%	14%	11%	20%

Company characteristics

Supply chain position	Raw material producer	Sub-subsupplier	Subsupplier	Supplier	Manufacturer to final customer
	0%	14%	24%	38%	24%
Number of employees	<25	26-50	51-100	101-250	>250
	38%	24%	17%	14%	7%
Number of persons working in process planning	1 to 2	3 to 5	6 to 10	>11	
	33%	40%	24%	2%	
Company age	1 to 5 years	6 to 10 years	11 to 20 years	>20	
	0%	2%	10%	88%	
Does the company belong to a company group?	Yes	No			
	31%	69%			
Company group size	<500	501 to 1000	1001 to 10000	>10000	
	22%	17%	17%	17%	
Performed machining operations by responding companies	Turning	Milling	Drilling	Turn-milling	
	88%	86%	90%	52%	
Does the company have any multi task machines?	Yes	No	Blank		
	88%	10%	2%		
Does the company have any other production than machining?	Yes	No			
	71%	29%			
Percentage of metal cutting?	A: 0-25%	B: 26-50%	C: 51-75%	D: 76-100%	
	17%	10%	24%	50%	

Homogeneity of products

Is products with free-form surfaces manufactured?	Yes	No	Blank
	48%	45%	7%

Machined materials		
	Steels	60%
	Stainless steel	45%
	Aluminium alloys	60%
	Copper alloys	36%
	Iron, cast iron	48%
	Titanium (and alloys)	10%
	Polymers	36%
	Hardened steels (tool steels)	12%

Respondent's characteristics

Respondent's profession	Process planner	Production manager or eq.	Production engineer/technician	CEO/owner	Other
	0%	0%	0%	0%	0%
Respondent's educational level	High School engineering	Bachelor of Engineering	Master of Engineering	Other education	
	0%	0%	0%	0%	
Respondent's process planning work experience	1 to 5 years	6 to 10 years	11 to 20 years	21 -30 years	Blank
	0%	0%	0%	0%	0%

Appendix B

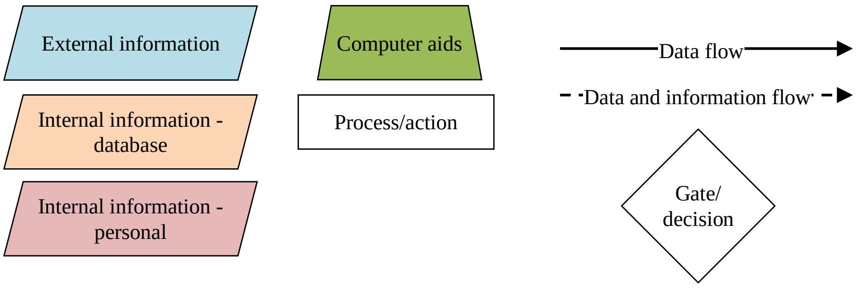

Figure 8.1 Survey2: Building blocks for flow charts.

Table 8.2 Survey2: Evaluation form for defining automation levels of process planning work.

Generation of tool paths	0.25	Manual NC programming
	0.5	Manual CAM programming
	0.75	Semi- automated CAM programming using predefined strategies
	1	Fully automated tool path generation - no manual interference
Tool selection	0.2	Manual tool selection (new each time)
	0.4	Manual tool selection (reuse of old tools no database)
	0.6	Manual tool selection (reuse of old tools w. searchable database)
	0.8	Semi- automated using wizards with suggested tools
	1	Fully automated tool selection - no manual interference
Machining parameters selection	0.2	Manual parameter selection (new each time)
	0.4	Manual parameter selection (reuse of parameters, no database)
	0.6	Manual parameter selection (reuse of parameters, searchable database)
	0.8	Semi- automated using wizards with suggested parameters
	1	Fully automated parameter selection - no manual interference
Fixture selection	0.2	Manual fixture selection
	0.4	Manual fixture selection (reuse of fixtures no database)
	0.6	Manual fixture selection (reuse of fixtures, searchable database)
	0.8	Semi- automated using wizards with suggested fixture
	1	Fully automated fixture selection - no manual interference
NC program verification	0.2	Online physical program testing
	0.4	Online operating panel control testing
	0.6	CAM simulation
	0.8	Virtual collision testing
	1	Virtual cutting process verification

Appendix C

Table 8.3 Survey 3: Compilation of questions, responses and categorisation index.

	Question	Response alternative	Response	Index
1	**What financial indicators are presently used to measure the company's performance?**	A. Turnover	50%	B
		B. Revenue	50%	
		C. Manufacturing cost	58%	
		D. Process planning cost	8%	
		E. Administrative cost (in relation to other financial measures)	0%	
		F. Added value (as performed by company)	8%	
		G. Other	0%	
1b	**Can any of the above performance indicators be transferred to process planning?**	A. Turnover	8%	B
		B. Revenue	25%	
		C. Manufacturing cost	50%	
		D. Cost for process planning	17%	
		E. Administrative cost (in relation to other financial measures)	0%	
		F. Added value (as performed by company)	8%	
		G. Other	8%	
2	**What non-financial indicators are presently used to measure the company's performance?**	A. Scrap rate	50%	B
		B. Customer complaints	33%	
		C. Machine down time	17%	
		D. Won orders	17%	
		E. Work in Process (WIP)	17%	
		F. Total manufacturing lead time	42%	
		G. Total process planning lead time	0%	
		H. All identified processes lead times are measured	8%	
		I. Other lead times	8%	
		J. Other	17%	
2b	**Can any of the above performance indicators be transferred to process planning?**	A. Scrap rate	42%	B
		B. Customer complaints	8%	
		C. Machine down time	0%	
		D. Won orders	0%	
		E. Work in Process (WIP)	0%	
		F. Total manufacturing lead time	8%	
		G. Total process planning lead time	0%	
		H. All identified processes lead times are measured	0%	
		I. Other lead times	8%	
		J. Other	0%	
3	**Is process planning well defined regarding work activities and roles?**	Yes	75%	D
		No	17%	
		Blank	8%	
4	**To what extent are customer demands represented in the organisation and in process planning specifically?**	Customer demands are communicated qualitatively to process planner	50%	A
		Customer demands are translated into product and production demands before reaching process planner	33%	
		Customer demands is defined as manufacturing cost demand	17%	
		Other	0%	
		Blank	8%	

5	**What is the understanding of company objectives in process planning phase? (E.g. are the relations between process planners' work and company objectives clarified?)**	Process planners have excellent understanding for their work in relation to company goals	50%	A
		Process planners have good understanding for their work in relation to company goals	25%	
		Process planners have less good understanding for their work in relation to company goals	8%	
		Process planners have poor understanding for their work in relation to company goals	8%	
		Process planners have no understanding for their work in relation to company goals	0%	
		Blank	8%	
6	**Is there any support for automated data collection of manufacturing data?**	Yes	58%	C
		No	42%	
		Other	0%	
		Blank	0%	
6b	**Is there any support for automated data collection of process planning work?**	Yes	25%	C
		No	67%	
		Other	0%	
		Blank	8%	
7	**Are the present performance indicators related to specific company objectives?**	Yes	58%	A
		No	33%	
		Other	0%	
		Blank	8%	
8	**Are the present performance indicators relevant?**	Yes	67%	A
		No	8%	
		Other	17%	
		Blank	8%	
9	**Are ratios used instead of absolute numbers when performance indicators are presented?**	Yes	50%	not incl.
		No	33%	
		Blank	17%	
10	**Is automatically collected performance data from processes used when possible?**	Yes	25%	C
		No	58%	
		Blank	17%	
11	**What are the company's performance measures based upon?**	Trends	25%	A
		Specific times	25%	
		Other	25%	
		Blank	33%	
12	**Is there a consciousness about process planning productivity?**	Yes	33%	E
		No	67%	
12b	**Is there a consciousness about process planning quality?**	Yes	25%	E
		No	75%	

Appendix D

Table 8.4 Survey 4: Production volumes and product value of responding companies.

		Statistic	Std. Error
Production volume for typical products	Mean	1725	1234
	Median	35	
	Std. Deviation	12280	
	Minimum	1	
	Maximum	120000	
	Valid cases	99 (69%)	
Product value [SEK] for a typical product (price to customer)	Mean	190144	1,58E5
	Median	335	
	Variance	1.11E12	
	Std. Deviation	1.05E6	
	Minimum	0	
	Maximum	7000000	
	Valid cases	44 (30%)	

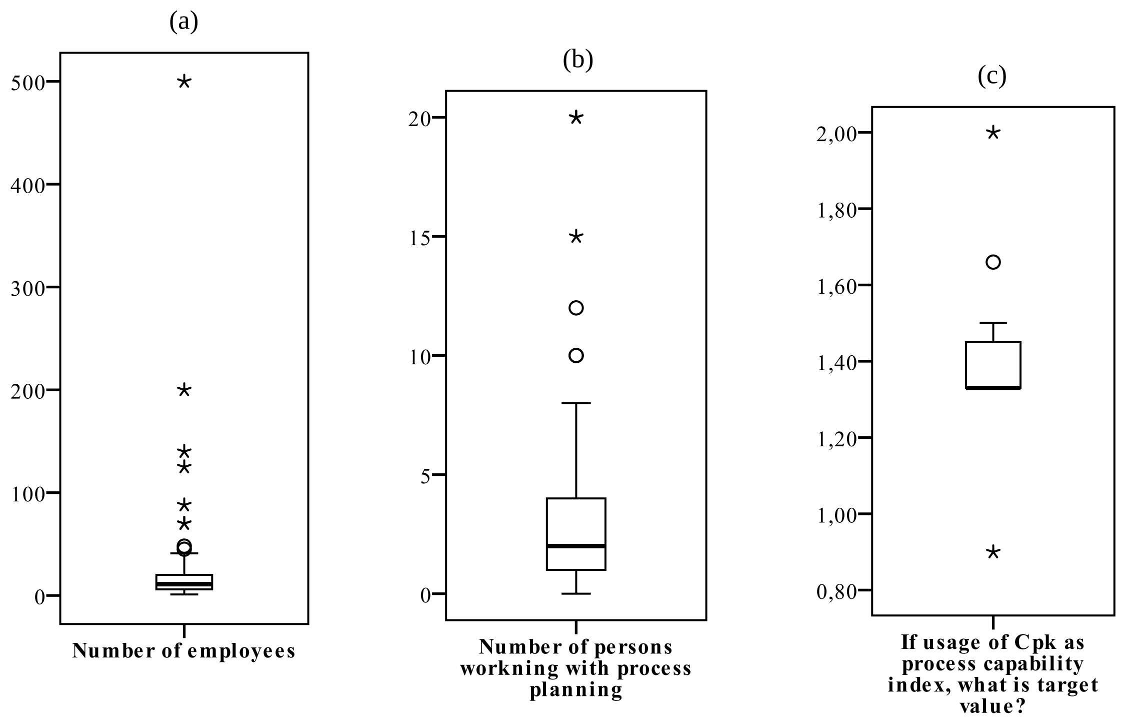

Figure 8.2 Survey 4: Boxplots of (a) number of employees, (b) number of process planners and (c) used target C_{pk}-value (12 respondents). Each percentile corresponds to 25%.

Table 8.5 Survey 4: Correlation matrix.

		Proportion of planned products available as 3D CAD models	Proportion of products prepared in CAM	Proportion of other data available digitally available	Proportion of process planning time dedicated to CAM programming	Product value [SEK] for a typical product (price to customer)	Production volume for typical products	Number of employees	Number of persons working with process planning
Proportion of planned products available as 3D CAD models	Pearson r	1	,569**	,329**	,445**	-,092	,070	,066	,223*
	N	144	144	144	144	44	99	140	132
Proportion of products prepared in CAM	Pearson r	,569**	1	,299**	,632**	-,114	,065	,107	,319**
	N	144	144	144	144	44	99	140	132
Proportion of other data available digitally available	Pearson r	,329**	,299**	1	,255**	-,228	-,003	,165	,147
	N	144	144	144	144	44	99	140	132
Proportion of process planning time dedicated to CAM programming	Pearson r	,445**	,632**	,255**	1	-,120	-,093	,047	,086
	N	144	144	144	144	44	99	140	132
Product value [SEK] for a typical product (price to customer)	Pearson r	-,092	-,114	-,228	-,120	1	-,047	-,078	-,112
	N	44	44	44	44	44	43	43	41
Production volume for typical products	Pearson r	,070	,065	-,003	-,093	-,047	1	,052	,005
	N	99	99	99	99	43	99	98	95
Number of employees	Pearson r	,066	,107	,165	,047	-,078	,052	1	,231**
	N	140	140	140	140	43	98	140	131
Number of persons working with process planning	Pearson r	,223*	,319**	,147	,086	-,112	,005	,231**	1
	N	132	132	132	132	41	95	131	132

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 8.6 Survey 4: Correlation matrix (companies with less than 2% 3D CAD use excluded).

		Proportion of planned products available as 3D CAD models	Proportion of products prepared in CAM	Proportion of other data available digitally available	Proportion of process planning time dedicated to CAM programming	Product value [SEK] for a typical product (price to customer)	Production volume for typical products	Number of employees	Number of persons working with process planning
Proportion of planned products available as 3D CAD models	Pearson r	1	,527**	,258*	,334**	,470*	,036	-,026	,272*
	N	91	91	91	91	26	67	91	88
Proportion of products prepared in CAM	Pearson r	,527**	1	,228*	,583**	,402*	,045	,063	,295**
	N	91	91	91	91	26	67	91	88
Proportion of other data available digitally available	Pearson r	,258*	,228*	1	,225*	,334	-,023	,127	,108
	N	91	91	91	91	26	67	91	88
Proportion of process planning time dedicated to CAM programming	Pearson r	,334**	,583**	,225*	1	-,046	-,144	-,002	,083
	N	91	91	91	91	26	67	91	88
Product value [SEK] for a typical product (price to customer)	Pearson r	,470*	,402*	,334	-,046	1	-,135	-,222	-,060
	N	26	26	26	26	26	25	26	26
Production volume for typical products	Pearson r	,036	,045	-,023	-,144	-,135	1	,042	,008
	N	67	67	67	67	25	67	67	66
Number of employees	Pearson r	-,026	,063	,127	-,002	-,222	,042	1	,299**
	N	91	91	91	91	26	67	91	88
Number of persons working with process planning	Pearson r	,272*	,295**	,108	,083	-,060	,008	,299**	1
	N	88	88	88	88	26	66	88	88

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Appendix E

The following section (equation A.1 and A.2 and Figure 8.3) explains the calculation of the unit normal deviate based on C_p/C_{pk}.

$$\Delta = x_{C_p} - x_{C_{pk}};\ x_{C_p} = \frac{6C_p}{2};\ x_{C_{pk}} = \frac{6C_{pk}}{2} \tag{A.1}$$

The constant 6 corresponds to the embedded 6 sigma in C_p and C_{pk} and this value must be divided in 2 since it is a double sided interval. This gives the $x_{max/min}$ as in equation A.2.

$$x_{max/min} = x_{C_p} \pm \Delta = 3C_p \pm 3(C_p - C_{pk}) \tag{A.2}$$

Notations are explained in Figure 8.3.

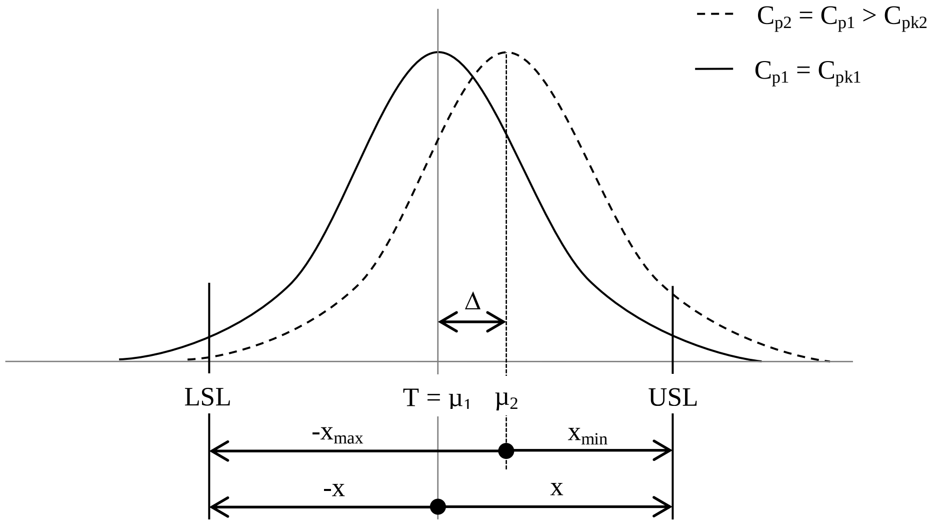

Figure 8.3 Difference between a centred process and a non-centred process.

Calculation of appraisal cost, C_A is given in equation A.3.

$$C_A = \frac{t_c}{n_c} \cdot K_m \cdot N \tag{A.3}$$

Where t_c is the automatically logged machine down time for manual in-process control, n_c is the total number of in-process controls based on part specification, K_m is the machine and operator cost rate, and N is the production volume.

Appendix F

Traditional cost components

The direct cost for the machine tool and the labour cost, C_m expressed by Kalpakjian and Schmid (2006).

$$C_m = t_m \cdot K_m \tag{A.4}$$

Where t_m is the machining time per produced piece - K_m is the machine tool and labour cost per minute as:

$$K_m = M_m + n \cdot L_m \cdot (1 + B_m) \tag{A.5}$$

Where M_m is the machine cost rate, L_m is the fully burdened labour cost for one machine operator (including overhead) – B_m the burden rate for the machine tool, including depreciation, maintenance, taxes and interest rate.

The set-up cost, C_s refers to the time required for preparing the machine tool for machining a batch of products:

$$C_s = \frac{K_m}{N} t_s \tag{A.6}$$

Where N is the production batch size and t_s – the set-up time.

The idle cost, C_i refers to the cost connected to loading/unloading of workpiece and adjustments:

$$C_i = K_m \cdot t_i \tag{A.7}$$

Where t_i is the idle time.

The direct tool cost, C_t comprises of insert cost and tool holder cost (Wiiburg-Bonde, 2000):

$$C_t = (\frac{K_h}{N_h} + \frac{K_i}{0.75i}) \cdot \frac{t_m}{T} \tag{A.8}$$

Where K_h is the cost of the tool holder, N_h – the tool holder life as the number of inserts, K_i – the insert cost, i is the number of cutting edges per insert, t_m – the machining time per piece and T – the tool life.

The indirect tool cost, C_{it} attributes to the time for tool changes due to tool wear (Wiiburg-Bonde, 2000):

$$C_{it} = K_m \cdot t_c \cdot \frac{t_m}{T} \tag{A.9}$$

Where t_c is the tool change time, t_m - the machining time per piece and T – the tool life.

The carbon emission signature as defined by Jeswiet and Kara (2008) is defined as:

$$CES^{TM} = \frac{1}{\eta} \cdot (\%C \cdot 112 \cdot \%NG \cdot 49 + \%P \cdot 66) \tag{A.10}$$

Where C is the ratio of coal, NG natural gas and P oil in the electricity generation grid. η is the efficiency of energy conversion.