

# PROCESS PLANNING METHODOLOGY GUIDE FOR INTERACTIVE LEARNING

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**Abstract:** Process planning is a central, knowledge extensive and important activity in a manufacturing company. During process planning, countless decisions are made, many times based upon the process planner's tacit knowledge, based on years of experience. The knowledge gap between the expert and the novice is wide. Narrowing this gap, taking the novice towards becoming expert, is an objective of education. This paper presents a solution for model-based interactive learning of process planning, validated through application in master level production engineering courses.

**Keywords:** Process planning, model-based interactive learning, knowledge reference model.

## 1. INTRODUCTION

Systematic process planning is a key enabler for effective product realization from design through manufacturing. Process planning is a central, complex and knowledge extensive activity. Countless decisions are made during process planning. Every process and operation must be designed in the best possible way to ensure that the overall process chain leads to the right product quality at low cost.

During process planning, several alternative solutions are usually evaluated. For the same manufacturing requirements there can be different process alternatives. In addition, there are interfaces to other production engineering domains within an organization interacting with process planning, e.g. product development, production equipment acquisition and factory design. Altogether, this means that process planning is more or less iteratively performed, rather than being a straight forward process.

Experienced process planners have no difficulties in managing the complexity of process planning compared to the novice who is facing significantly bigger challenges. Grasping the scope and understand the type of decisions made in process planning is difficult. Many years of experience enables the expert to make the right decisions. The rational reasoning in making these decisions is often based on tacit knowledge. Quite naturally, the knowledge gap between the expert and the novice is wide (Fig. 1.).

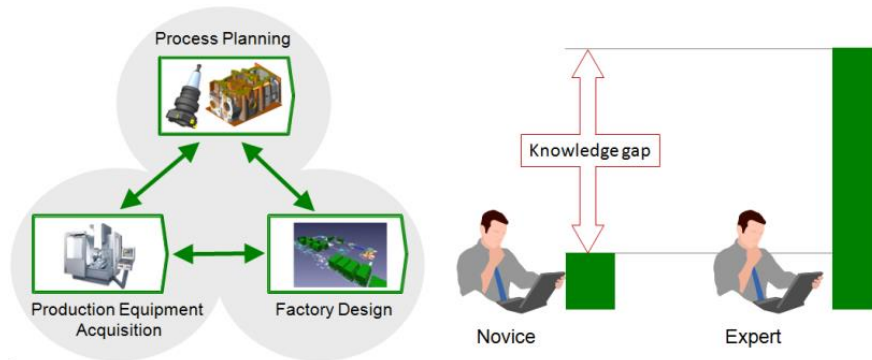


Fig. 1. Process planning is a knowledge extensive process with many interactions.

Narrowing this gap, taking the novice towards becoming expert, is an objective of education. To visualize the activities of process planning, and the interaction between other activities in the production engineering domains, can be a key element in process planning education, and very important for achieving good understanding of the subject. This puts demand for efficient tools and methods for learning process planning in engineering education.

## 2. RESEARCH APPROACH

### 2.1. Problem statement and research question

The process planner is a problem-solver who applies his knowledge about manufacturing in designing a solution, namely, the process plan. In similar to design, there is no single solution, but rather a variety of possible solutions which surrounds a broad optimum. There are several reasons for initiating process planning, e.g. new or changed design of product, new or changed manufacturing approach/strategy, manufacturing methods, machine tools, flow balancing and bottle neck elimination, quality issues, continuous improvements activities etc. The width and scope of process planning may vary, from participation in design of a new factory to micro level optimisation of a machining operation. Effective collaboration between other production engineering domains is important. Decisions made during the early stages of production have big impact on the final manufacturing cost and lead time. Many activities are interrelated and affect one another. Naturally this complexity puts up challenges for education. Therefore, the main research question is:

*What activities, objects and relationships should be represented in a holistic activity model for process planning, and how can the model be used to facilitate efficient learning?*

### 2.2. Research method

Methods used in this research has been a collection of existing knowledge and proven experience in the industry, identification and study of state-of-art technology and research in the area of CAPP/CAM. The knowledge base of this research is big. Besides the large number of presented publications within the research field, industry work processes have been studied at the companies; Scania, Volvo, Sandvik Coromant, Xylem (former ITT-Flygt) and Dynamate, as well as at several other large and small manufacturing companies. Knowledge of experienced professionals has been collected through interactive collaboration in form of workshops during the development of the activity model. Survey of research in the area has been done through literature studies and through collaboration in the development of international standards for information modeling in manufacturing. Activity modelling have been used to model the decisions, actions, and activities of process planning. The activity model has been designed in an iterative way. Through joint discussions, the model has been continuously enhanced and improved. Draft models have been presented and evaluated at workshops where industry experts have provided feed-back.

## 3. LITERATURE STUDY

### 3.1. What is process planning - definition and scope

Even though manufacturing of products in an industrial way can be traced back very early in history of man and society, the activity of process planning still lacks a common definition. Process planning is a key area for manufacturing which has been studied within the international academy for production engineering, CIRP since

its formation in 1951. The CIRP definition, as given in the CIRP dictionary (2004) is quite broadly drafted and has a rather large scope. CIRP defines process planning as an activity which;

*“Includes all planning measures to be taken once to ensure the production of a part, an assembly or a final product at the lowest cost and best quality, which are mainly interpretation of the part design data, selection of the manufacturing processes and process optimization, determination of the routing plans as well as planning of the means of production and manpower assignment.”.*

As literally thousands of journal papers and conference publications related to process planning have been presented during the last four decades, only some examples of definitions will be presented here. Three significant characteristics of process planning a lot of them have in common are the emphasis on; the link between design and manufacturing, the large number of decisions, and the output in terms of instructions and NC-programs. Weill et al. (1982) states that process planning is a particular important activity that should be distinguished from other planning activities in the manufacturing system. Fainguelernt (1986) stresses the high number of choices in process planning that set the machining conditions as; selection of jigs and fixtures, selection of machine tools, sequencing of operations and determination of manufacturing dimensions and tolerances. Ham and Lu (1988) define process planning as the coordinating link between the intention of design engineers and those of manufacturing engineers in a production environment”. Denkena et al. (2007) emphasises the central role of process planning in manufacturing and states that process planning is one of the most important steps in converting a design concept into a manufactured product. In contrast to above examples of definition of process planning, the international standard ISO 10303-240 (2005) has a much narrower definition where process planning is about identifying the manufacturing steps necessary to transform the material specified by the design into a product. The resulting process plan is a set of instructions used by programmers to generate machine tool controller programs to remove material. In general, the definitions given in publications are quite briefly described. A more extensive work about process planning has been made by Halevi (2003) in the book, Process and Operation Planning – Revised Edition of The Principles of Process Planning: A Logical Approach.

Regarding the scope of process planning, the borders between design, process planning and manufacturing are not clear and precise. In its broadest sense, process planning spans from generic or conceptual planning (finding suitable technology for producing a feature, a part or a product) to detailed operation planning (defining operations, determining detailed process parameters and required tools, defining setups and operation sequence, resources etc.). The latter, detailed planning is in research referred to as micro-planning (or operation planning), while the former, more comprehensive level of planning is referred to as macro process planning. Operation planning is considered as the most detailed level serving as a link between planning decisions and actual manufacturing operation. Generic planning and macro-process planning serves as the critical link between design and manufacturing. (ElMaraghy, 1993)

Conceptual process planning is an activity of assessing the manufacturability and estimating the cost of conceptual design in the early product design stage. This activity supports product design to optimize product shape, configuration, and material selection to minimize the manufacturing cost. Conceptual process planning aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs and time. (Feng and Song, 2000)

Sivard and Lundgren (2008) present a different and additional perspective on conceptual process planning, when compared with (Feng and Song, 2000), and emphasizes that conceptual process planning necessarily not is a clearly-defined phase that takes place prior detailed process planning. Process planning is conceptual as long as there is unambiguous or contradictory information about what to be produced, how and with what. Such "conflicts" are temporary solved by making assumptions. Depending on the actual situation there can be more or less unambiguous or contradictory information and during the conceptual phase the process plan is a key interaction object between process planning, factory design and production equipment acquisition activities. As a process plan can be revised on request from factory design or production equipment acquisition, the process plan is not fixed. Due to restrictions caused, or opportunities offered, by physical resources as equipment or buildings, it might be desirable to change the process plan in order to achieve the holistically best possible solution.

#### 4. EDUCATIONAL PERSPECTIVE ON PROCESS PLANNING

Being a research area for at least four decades means that process planning has been extensively explored, especially regarding the possibilities to automate it. The introduction of computers during the early 1960s made industry to see the potential of using them for process planning and production scheduling. According to Altung & Zhang (1989), quoted in numerous following papers, B. W. Niebel is recognized as one of the first who

discuss usage of computers in Process Planning. In the paper “Mechanized Process Selection for Planning New Designs” (1965) Niebel describes a process selector guide aimed to assist technical personnel in the selection of basic processes to be used to manufacture a given functional design at a minimum cost with regard for quality, quantity, service, and reliability requirement in order to determine the optimum manufacturing processes. Note that Niebel actually doesn’t speak about a process planning system. Since then, a vast number of publications regarding process planning automation have been published. In the late 1980s and during the 1990s there was a belief that advanced software, artificial intelligence, database management, and communications technology could be used to automate the knowledge work of the factory. Today, it is no exaggeration to state that the once so high expectations regarding process planning automation, so far has failed to be realized. Xu et al. (2010) has presented a comprehensive up-to-date review of the CAPP research works. They conclude that many difficulties have been experienced by the researchers in attempting to implement artificial intelligence techniques in CAPP, and that these difficulties still remain unsolved. As pointed out by Huang et al. (2002), the enormous complexity associated with the task of process planning is probably one big reason that hinders the application of CAPP systems. Replacing experienced process planners through automating their work in CAPP is probably not possible. But, provided with a well defined problem space and necessary rules for decision CAPP systems can be used similar to how design configuration software applications are used for the creation of new product variants based upon a well defined product program. For instance; manufacturing of tailor made cutting tools at Sandvik Coromant or manufacturing of power transformers at ABB.

#### 4.1. Process planning, a design activity

Literature studies, observations and field studies of process planning in industry clearly shows that process planning is an activity where human expertise only partially can be replaced by “intelligent” computer applications. In the preface of the book, *The Principles of Design* (1990), the author, Nam P. Suh writes; “*Engineers design. They design structures, products, software, manufacturing processes, systems and even organizations. The decision that they make during the design stage profoundly affect all those that follow.*”. This includes, and is true, for process planning too, which definitely is an act of engineering. Or by rephrasing the Oxford English Dictionary (2014) definition of engineer; a process planner is a person who uses specialized knowledge or skills to design, build and maintain complicated equipment, systems, processes, etc.

According to Suh, the design process is characterized by two distinctive processes: the *creative process*, where ideas or solutions are synthesized, and the *analytical process*, where decisions must be made by evaluation of proposed ideas. The creative process is subjective, and depends on the person’s knowledge base and creativity. For the same set of requirements, virtually an infinite number of possible creative solutions can be synthesized. The analytical process is however deterministic and based on a finite number set of basic principles. These two processes are interrelated, since one must be able to abandon or discard bad ideas quickly to enable the creation of new ideas by exploring different possibilities. This is also true for process planning which in many aspects can be considered as a design process where the process planner many times has to be creative to define a suitable manufacturing process for a certain product and manufacturing conditions.

#### 4.2. Knowledge framework for efficient learning

There is a big difference between the way a novice and an expert acts. Where the novice calculates, using rules and facts for determining actions (just like a computer following a program) the expert not only sees what needs to be achieved, he or she also sees immediately how to achieve this goal (Dreyfus and Dreyfus, 1986). Developing expertise takes time, but if students are given the possibility to apply knowledge and practice their skills on real problems, and ultimately also create a product, through all steps in the manufacturing realisation process, they can develop basic competence in process planning as an outcome of learning. A well structured learning supportive framework is here very useful for achieving this development in education. To support learning efficiently, this framework is based upon an activity model that describes the activities, objects and relationships in process planning. Through the semantic of the activity model, examples, rules and guidelines, a way of thinking in process planning is conveyed by the framework.

Even though it has shown to be very difficult to automate process planning, CAPP research has resulted in knowledge about rules and praxis’s that can be applied for explaining decision making in process planning. (Fig. 2). Park (2003) suggest a knowledge capturing methodology in process planning based on four knowledge elements; *facts, constraints, way of thinking* and *rules*. Facts cover all data objects, and constraints correspond to the technological requirements of process planning. The “way of thinking” is a logical procedure for quickly decreasing the solution space. Rules are key parameters that control the way of thinking. Naturally, the capability of resources (machine tools, cutting tools, etc.) might change as technology evolves over time. Such changes will also affect the validity of the rules applied in process planning.

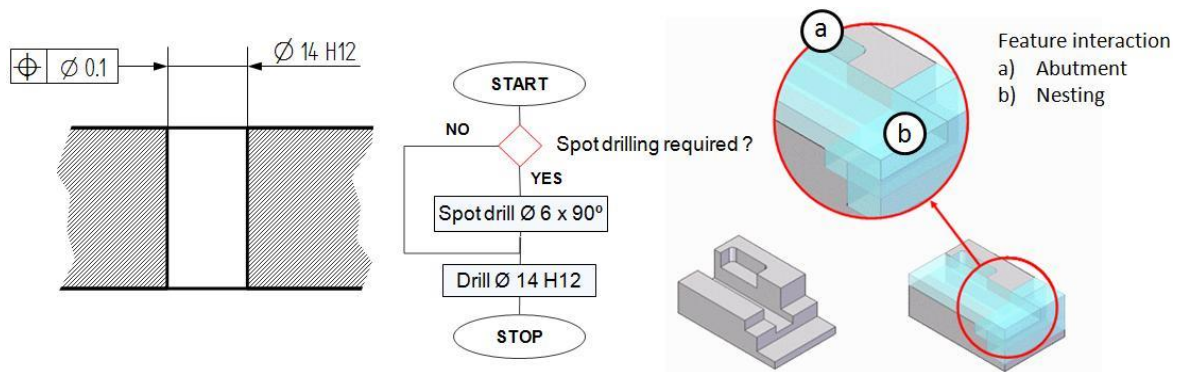


Fig. 2. Examples of rules and praxis's to support decision making in process planning.

In process planning for machining, process selection, operation sequencing and setup planning can be considered as fundamentally important activities. For process selection and setup planning, manufacturing feature information, Geometric Dimensioning and Tolerancing (GD&T) and other types of Product Manufacturing Information (PMI) of a workpiece are used to design appropriate machining processes, machining and setup sequence.

Loosely and strictly related tolerances, and their effects on setup planning, as described by Stampfer (2009), is a way of describing the “way of thinking” for setup planning. In operation sequencing, manufacturing interactions, as described by Faheem et al. (1998), is a way of managing operation precedence constraints in a rational way. The authors divide the interactions in two categories, hard and soft constraints. While the latter are constraints which affect the quality, cost or efficiency of a plan, the former are constraints which affect plan feasibility. Here, manufacturing features, and manufacturing interaction, divided into hard and soft constraints, is a way of represent and communicate the “way of thinking” for operation sequencing.

Liu and Wang (2007) present an approach for feature sequencing for machining of prismatic parts based on feature information. Machining sequence is determined using knowledge-based rules, such as that features with the same tool approach direction shall be clustered into the same setup, and geometric reasoning rules, such as geometric adjacency interactions (nesting and abutment) and volumetric interactions, illustrated in Fig.2. Such reasoning is an additional contribution that supports to convey “way of thinking” for process planning.

## 5. RESULTS

The main result of this research is a web-based guide for model-based interactive learning (Fig. 3.). The purpose with the web-guide is to communicate WHAT process planning is (in terms of activities, objects and relationships), and HOW process planning is performed (in terms of textual information, supported by images, detailed descriptions and examples). Learning is facilitated by different kind of functionality in the web-guide. By clicking on activities and objects in the web-guide, or using the in-built search engine, a user can browse the web-guide and search for information in a free manner. Each activity in the web-guide can have one of several relationships to other activities in other engineering domain, represented through interaction-objects. The interaction-object is a common object that is shared between several activities. The interaction-objects provide ability for users to investigate activity relationship from different views. This ability makes the web-guide become more than a tool for facilitating learning. The web-guide can also support cooperative work in manufacturing system development, e.g. communicate a project's current state between Process Planning, Production equipment acquisition and Factory planning and design. The web-guide is easy configurable and adaptable which allows design of specific guides that are tailor-made for a specific learning purpose.

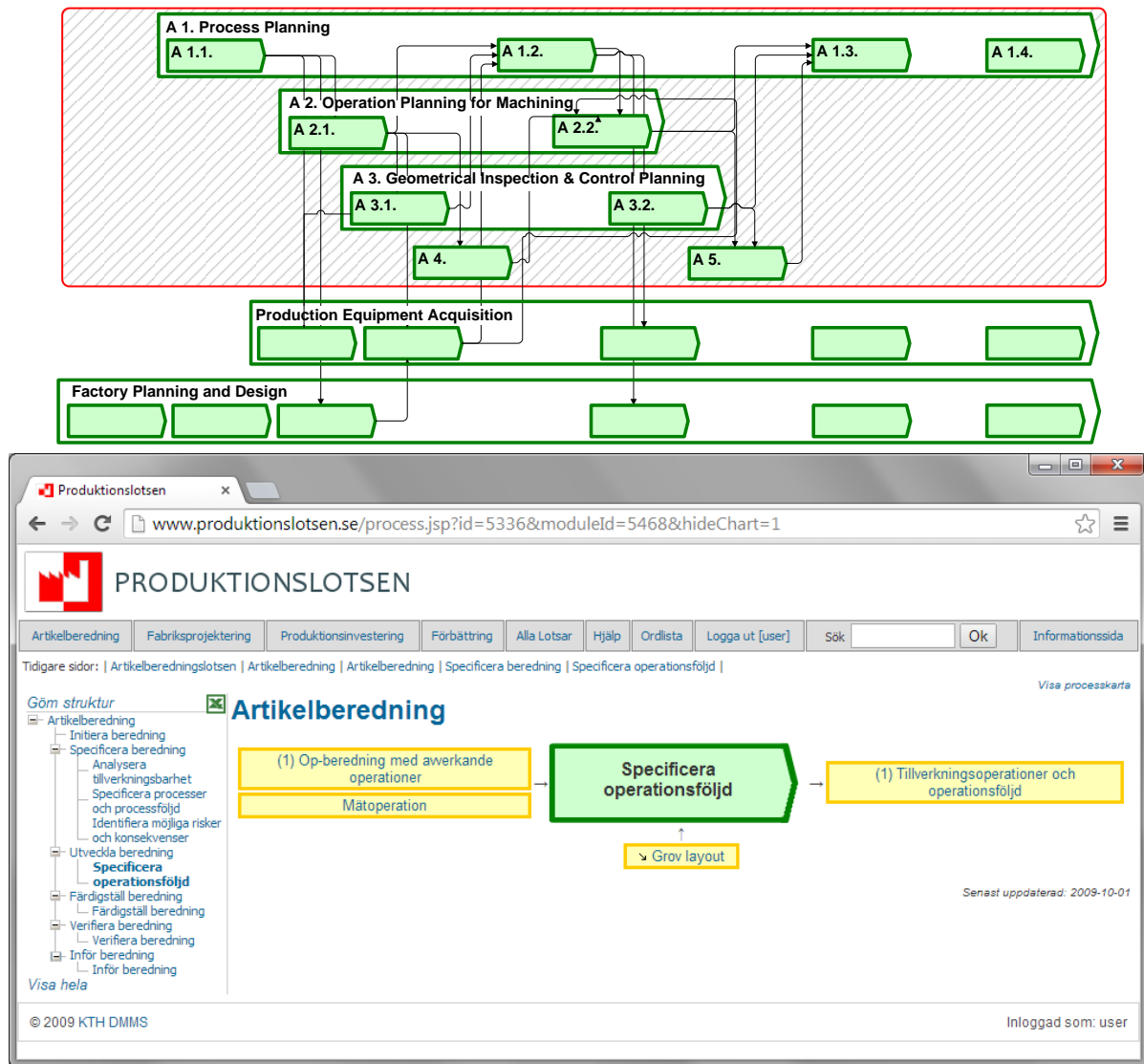


Fig. 3. A screenshot from [www.produktionslotsen.se](http://www.produktionslotsen.se) (Swedish text).

Fig. 4. A high-level schematic activity model of the work processes of the web-guide.

The activities, objects and relationships in the web-guide represent domain knowledge within process planning. The web-guide can be considered as a knowledge reference system but it doesn't contain any intelligence which allows it to perform reasoning or to provide context based and user depending suggestions. Furthermore it has no learning capabilities; a human must update its content. The core of the web-based guide are computer interpretable activity models which represents different process planning related work processes (Fig. 4). Each activity model can be further broken down in sub-activities. As for instance, A 2. *Operation planning for machining* in Fig. 4. contains following activities:

## A 2. Operation planning for machining.

**A 2.1. Specify machining operations:** Analysis of the product to be manufactured, defining machining features, machining operations, machining directions, operation and setup sequence etc.

**A 2.1.1. Identify machining features:** Machining Features are geometric entities of a workpiece which has semantic significance from a machining point of view. Meaning that the geometric shape of the feature can be manufactured via one or several machining operations.

**A 2.1.2. Specify operation:** A machining operation is a combination of a process and a cutting tool used for machining of a feature.

**A 2.1.2.1. Specify process:** Material removing manufacturing methods, e.g. milling, drilling, turning, boring, etc.

- A 2.1.2.2. **Specify cutting tool:** Milling and drilling tools, etc. For instance, face mill, end mill, drill, boring tool, turning tool, and many more.
- A 2.1.2. **Specify operation sequence:** The precedence order in which the operations are executed. For determining the operation sequence, rules as defined by Faheem et al. (1998), Stampfer (2009), and Liu and Wang (2007) can be used.
- A 2.1.3. **Specify setup:** Clustering of operations that have similar tool approach directions.
  - A 2.1.3.1. **Specify clamping:** Determine what kind of clamping that is appropriate. If no standard fixtures, such as vise or chuck, are possible to use, a dedicated fixture may have to be designed. In that case, it will be a subject for A 4. *Fixture development and design*.
  - A 2.1.3.2. **Specify machine:** Depending on operations and workpiece shape, different type of machine tools are appropriate. Workpieces can be categorised as either being prismatic, rotational or prismatic (Waiyagan and Bohez, 2005). Prismatic workpieces are typically manufactured by milling operations, while rotational workpieces are machined by turning operations. Prismatic workpieces contains both prismatic and rotational features, and can often be completely machined in a multi-axis lathe with live tools.
- A 2.2. **Develop machining operations:** Synthesis, detailing and optimization of previous performed planning, process design activities.
  - A 2.2.1. **Define cutting tool:** Specify the detailed parameters of selected cutting tools.
  - A 2.2.2. **Define operation parameters:** Specify spindle speed, feed rates, cut depths, machining strategies, etc.
  - A 2.2.3. **Optimise machining sequence:** Which for instance can be, adjusting the clearance plane to reduce unnecessary air movements, fine tuning of toolpaths, and many more.

The activity models are linked together by interaction-objects. For instance, the output of activity A 2.1., *Specify machining operations* is an interaction-object between A 3. *Geometrical control and inspection planning*, A 4. *Fixture development and design*, and *Production equipment acquisition*. The output from A 2.1., information about selected machining operations, operation precedence, machining processes, cutting tools and machine tools, is used to determine inspection frequency, and for development of appropriate fixtures. It is also important when specifying what kind of machining processes a new machine tool must be capable to perform.

The size and the vast content of this knowledge reference model make it impossible to cover all aspects of the web-guide in detail in this paper. Some of the web-guides in Fig. 4 have been presented in other research publications, such as *Factory planning and design* (Chen, 2012), *Work instruction development* (Lundgren et al., 2008), and *Geometrical control and inspection planning* (Lindqvist, 2011). For a more detailed study, the full guide for process planning (*Artikelberedningslotsen*) is available online via [www.produktionslotsen.se](http://www.produktionslotsen.se).

### 5.1. Validation of research result and knowledge contribution

The activity model of this research has been cooperatively developed together with industry partners within the MERA program and the ModArt project (2006 – 2009). Validation of the activity model has been done in both national, as well as in international collaboration, and through its application in master level production engineering courses at KTH Royal Institute of Technology. The research has contributed to the development of the international standard ISO 10303 (STEP) within ISO TC184 SC4 WG3 T24 (the STEP development team for manufacturing application). Through this collaboration the research has been internationally recognized. For instance, in 2009 when part of the research was rewarded by Boeing Cooperation as recognition of exceptional performance and important contributions for utilization of STEP in manufacturing.

## 6. CONCLUSIONS

The presented holistic activity model of process planning has served an important role as knowledge reference model in master level production engineering education at KTH. Though the presented guide for process planning is very comprehensive, new manufacturing methods, tools etc will require further development of the guide to keep the content up to date with current technology, knowledge, work methods and praxis.

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