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Process Design as Fundament in Efficient Process Planning

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Abstract

Process planning is the activity of determining the manufacturing operations needed to produce a product. The knowledge work of process planning has been thoroughly investigated. Several ideas to automate process planning have been proposed but their success in practice has not yet been realized. Little attention has been given to design as an inevitable element in process planning and the role of human expertise in process design. From the premise that competent planners are a primary source of productivity this paper discusses process design, the role of human expertise and how CAPP systems could support human decision making.

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Keywords: Process Planning, Process Design, Human-Centered, CAPP

1. Introduction*

As being research subject for decades numerous publications related to process planning and CAPP have been presented, e.g.; Niebel [1], Egelie [2], Weill [3], Ham [4], van't Erve [5], Alting [6], van Houten [7], ElMaraghy [8], Kiritsis [9], Halevi [10, 11], to mention some few. Process planning may encompass different activities, strategies and methods depending on situation. There is no commonly adopted or standardized definition of what is included or not, nor for the activities whatever they may be. Type of parts, production rate, annual volumes, company

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strategies, etc., gives different possibilities and constraints for process planning [12]. Despite big efforts regarding process planning automation in CAPP research, initially stated expectations have yet not been realized in practice. At the same time not so much attention has been given to the role of design as an inevitable element in process planning and the role and value of human expertise in process design. Experienced process planners are valuable assets whose skills could be utilized better if supported by CAPP software capable to capture and represent design intent with manufacturing processes.

2. Computer-aided process planning

Computer-aided process planning (CAPP) is the use of computer technology to support or perform process planning. The knowledge work of process planning has been thoroughly studied within CAPP research. Several proposals to process planning automation have been presented since Niebel's [1] process selector guide for selection of optimum processes for manufacturing. Halevi [11] has concluded that CAPP research has resulted in numerous experimental CAPP systems which however have had no significant effect on manufacturing planning practice. Bagge [12] suggests that one cause behind unsuccessful implementation of CAPP in industry is a still un-bridged gap between industry needs and CAPP research´s understanding of process planning practice.

2.1. Human intervention, a source to problems supposed to be solved by CAPP?

Process planning has a fundamental role in the manufacturing system. Process planners design processes, and the decision they make profoundly affect those that follow. Every operation in the manufacturing process must be designed in the best possible way to ensure the overall process chain to bring forth products of intended quality at a competitive price. Understanding the process planners' role in efficient manufacturing and how to support planners' need is essential in development of efficient CAPP software but human intervention has in some CAPP research been regarded as a source of problems which can be eliminated by CAPP. Khoshnevis [13] states that human process planning is a; inefficient, subjective, lengthy, and tedious task prone to end up in inconsistencies and errors. Minimum human intervention also seems to be a goal for Suh [14] who sees STEP-NC (ISO 14649) [15] as a new paradigm enabling intelligent CNC controllers capable to perform process planning tasks as; recognize machining features, determine operations, operation sequence, set-ups and fixtures etc., with minimized human decision and interaction.

2.2. Unsolved challenges of CAPP

Process planning may at a first glance look rather straight forward to automate but the task have proven to be significantly more difficult in practice. The large number of decisions, the amount of information to consider, decisive, conflicting and non-commensurate factors, in combination with uncertain, ambiguous, imprecise information, makes the task complex. Feature recognition, operation sequencing and setup planning are core activities in CAPP which also has proven very complex and difficult to manage in research. Besides each activity is challenging by itself, complexity increases due to their mutual interrelation and the iterative manner in which they are performed. Usually no single optimal solution exists; rather a set of alternative solutions. Trying to determine an optimal manufacturing process under such circumstances, considering every possible and relevant aspect, usually results in a huge solution space. Feature recognition, operation sequencing and setup planning are known for ending up in complex combinatorial optimization problems considered as NP complete, which for instance have been addressed by Reddy [16] and by Ming [17]. Many different approaches such as; knowledge-based rules, graph-based, fuzzy-logic, artificial neural networks, evolutionary algorithms, hybrid approaches combining different technologies, etc., have been investigated but the difficulties have remained unsolved.

Although the generative process planning approach as described in [3, 4, 5, 6, 7, 8, 9, 10, 11] have not yet been fully realized, CAPP systems provided with a well-defined problem space and necessary rules for decision-making can be used in a similar way as product configuration software applications. One example is manufacturing of tailor made cutting tools at Sandvik Coromant, using in-house developed CAPP software. The very large number of possible product variants in combination with ever increasing demands for customized products in smaller batches with shorter lead-time makes manual process planning virtually impossible. Hence a high degree of automation in both manufacturing as well as in process planning is necessary for staying profitable and competitive. The in-house developed CAPP software is tightly integrated with SIEMENS NX in which all 3D product models, drawings, NC and CMM programs for machining and quality assurance are created automatically.

2.3. Humans - source to problems or irreplaceable component in manufacturing systems?

The thought that human intervention is a problem which should be minimized by application of STEP-NC is in a sense an irony. Even though STEP-NC enables unambiguous representation of information from various sources as CAD/CAM, CNC, etc., tasks such as setup and clamping decision-making, determination of operations and operation sequence, etc., are not part of the standard. In fact, some of the very first to discuss the application of STEP-NC, Brouër [18] and Weyrich [19], saw the technology as a mean to enable machine operators to make use of their expertise rather than replacing them. They envision STEP-NC based autonomous CNCs, which by means of a fully interactive graphical user interface supports NC-planning and programming more efficiently enabling, as Brödner [20] expresses it; "new ways of combining the unique capabilities of humans with the performance of machines".

Human skills are far from being obsolete in the era of Industry 4.0. Intelligent automation and reorganization of labor work will change the role of workers towards coordinators and problem-solvers. Smart technology will enable humans to realize their full potential as strategical decision-makers and flexible problem-solvers. Humans will still remain irreplaceable as being the most flexible component of the cyber-physical manufacturing system [21, 22]. Human skills are by no means a disappearing residual but a necessary ingredient for efficient production; and the irony of automation by Bainbridge [23] holds true: the more automated a system becomes, the more relevant human expertise becomes.

3. Machine expertise and human expertise

Completely automated process planning has not yet become fully realized despite many attempts to formalize the "know-how" of process planning, and the application of artificial intelligence in CAPP for problem solving and decision-making. One already mentioned reason is the large solution space caused by the complexity and level of uncertainty in process planning. Another possible reason is the difficulty to capture expertise in a rational way.

Human expertise and machine expertise are of different kind and the way they gain their expertise is also different. Machine expertise is a representation of declarative knowledge, which can be articulated, represented and mediated via symbols, expressed as heuristic rules, etc.

However, declarative knowledge is just one part of the process planner's knowledge. Process planning expertise evolves as described by Dreyfus [24] from a novice stage where actions are determined by calculation, using rules and facts, to an expert stage where one not only sees what needs to be achieved, but also immediately sees how to achieve this goal. As Hallevi [11] explain; process planners develop their knowledge from the experiences they obtain through practical work where processes are defined, follow-up is made, and corrective measures are taken during production. Experience is gained from problematic processes where parts are rejected and corrections are made to obtain a successful result. Using Polanyi´s [25] terminology, the process planner´s knowledge evolves through their experiences from conscious propositional and theoretical knowledge into practical, and tacit knowledge, which, as emphasized by Göranzon [26] is not susceptible to systematization in the same way as theoretical knowledge.

4. Process plan design

Engineering design theory and design methodology has attracted attention in research and yielded a considerable number of results. One of the most widely cited in research is Nam P. Suh´s axiomatic design theory and method

[27]. The design process is, according to Suh [28], characterized by two distinctive and interrelated processes; the creative, and the analytical process. The creative process is subjective, and depends on the person´s knowledge base and creativity. Virtually an infinite number of possible creative solutions can be synthesized for the same set of requirements. The analytical process is deterministic and based on a finite number set of basic principles. These 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.

Process planning is a design process too as process planners design sequences of operations conducing to intended ends. Every operation must be designed in the best possible way to ensure the overall process chain to bring forth products of intended quality at a competitive price. Ham [4] states that planning in a generic sense can he viewed as: the activity of devising means to achieve desired goals under given constraints and with limited resources. Poser [29] defines means as: processes or artefacts which fulfill some function in bringing something to an end. There are normally many sufficient means to choose between with respect to conditions such as; technological realizability, disposability of means, know-how of actors with respect to the means, etc.

4.1. Functions

Engineers design products and systems which perform functions. Function; a key concept in design theory, is by Rosenman [30] defined as; the action of performing, the mode of action by which something fulfills its purpose. As stated by Chandraskaran [31], functions may be intentional and non-intentional. The latter can be of positive or negative benefit and are conceptually regarded as “side effects”, i.e. something which is non-intentional but nevertheless occurs. As a manufacturing process can be viewed as a system whose function on macro-level is to transform a rawpiece into a product, function is also fundamental in process planning. In a well-designed process every single operation has a purpose in the sense it performs an intended function. Knowing the intention with an operation, its role and function in the larger context, and possible interaction with other operations is essential to avoid costly sub-optimization of the manufacturing process. As well as manufacturing operations performs intentional functions they occasionally perform non-intentional functions. For instance: The intentional function of hardening is to increase resistance to plastic deformation of the workpiece but a non-intentional, nevertheless occurring side effect of hardening is shape deformations and residual stresses.

4.2. Behavior

Behavior is how something acts in response to its environment. For Rosenman [30] function is related to behavior as the latter is the mechanism by which the former is achieved, i.e. function is the result of the behavior. Objects and processes, natural as well as artificial ones, exhibit behaviors which produce functions which can be utilized in a purposeful way. For instance, the location surface of the solid jaw of a vise exhibits the behavior of verticality enabling the function of perpendicular alignment of a workpiece against the machine tool spindle axis.

Thinking of process planning as an activity of devising means that fulfill functions makes it more apparent why means, as Poser [29] explains it, can be substituted with other and completely different means, which anyway can fulfills the same function, e.g. as replacing workers by industrial robots. However, as emphasized by Poser [29] the function itself cannot explain its role in being a mean to some end we must know the intention behind to evaluate its efficiency.

4.3. Purpose

Purpose is related to rationale as purpose is the reason for which something is done, created or exists. The relation between purpose, function and behavior as expressed by Rosenman [30] is that; purpose is enabled-by function which is achieved-by behavior. Knowing the purpose with an operation or its outcome is valuable in analysis activities as Process Failure Mode and Effect Analyzis (PFMEA). If an operation or its outcome lacks a explicit purpose, analysis is required to figure it out. Can the operation be removed without consequences in terms of product or process failure? Operations which lack purpose or does not fulfill any intended function are most likely unnecessary and can be considered as waste. However, when working in the opposite direction, when designing processes, the primary question for experienced processes planners is “what can possibly go wrong? In what way can the intended function of this operation fail?”

Treating process planning as a design activity where process planners´ intentionally design manufacturing processes with expected capability in an anticipated manufacturing environment enables application of fundamental principles for design in process planning. Different alternatives can be analyzed in a more rigorous and systematic way, etc.

4.4. Features – artefacts with meaning related to human values of utility

To determine what to remove and how to remove it is a core activity in process planning. The concept of features is fundamental in CAPP as being shapes which are supposed to have some meaning. For instance as in CAM-I [32] where feature is defined as; “a physical element of a part that has some specific engineering significance”. Originally proposed as a partial solution to the problem of automated process planning [33, 34] feature recognition has since Kyprianou’s [35] pioneering work on shape classification been a key issue in CAPP research. Effective feature recognition is a prerequisite for automatic selection of machining processes and cutting tools, setup planning and operation sequencing. Corney [36] mention that lay people have hard to comprehend why something that humans do rather effortlessly, is so difficult to implement in computer algorithms. However, as concluded by Verma [37] major challenges as; recognition of intersecting features and handling of multiple interpretations are still open research issues.

Besides the technical challenges of feature recognition, Rosenman´s [30] reasoning about purpose, function and behavior, contributes to explain why something experienced process planners do rather easy is so difficult to implement in CAPP systems. Interpreting part geometry in terms of manufacturing processes is a matter of practice. If recognition of shapes is a challenge an even bigger challenge must be to figure out the meaning of a shape. As Rosenman [30] explains, meaning with artefacts is related to human values of utility in a particular socio-cultural environment. Humans relate to artefacts through their purpose but artefacts do not have any intrinsic purpose except as assigned to them by humans or in relation to human concerns. By nature of their existence, artefacts exhibit behaviors which produce functions which can be utilized. If an artefact is taken out of its socio-cultural environment, it will continue to behave and function in the same physical way but its purpose might change as it is related to human values of utility in a particular socio-cultural environment. In practice it means that artefacts can be assigned new purposes different from those initially assigned by the creator of the artefact due to that they exhibit behaviors which produce functions useful in the particular socio-cultural environment in which the artefacts are used.

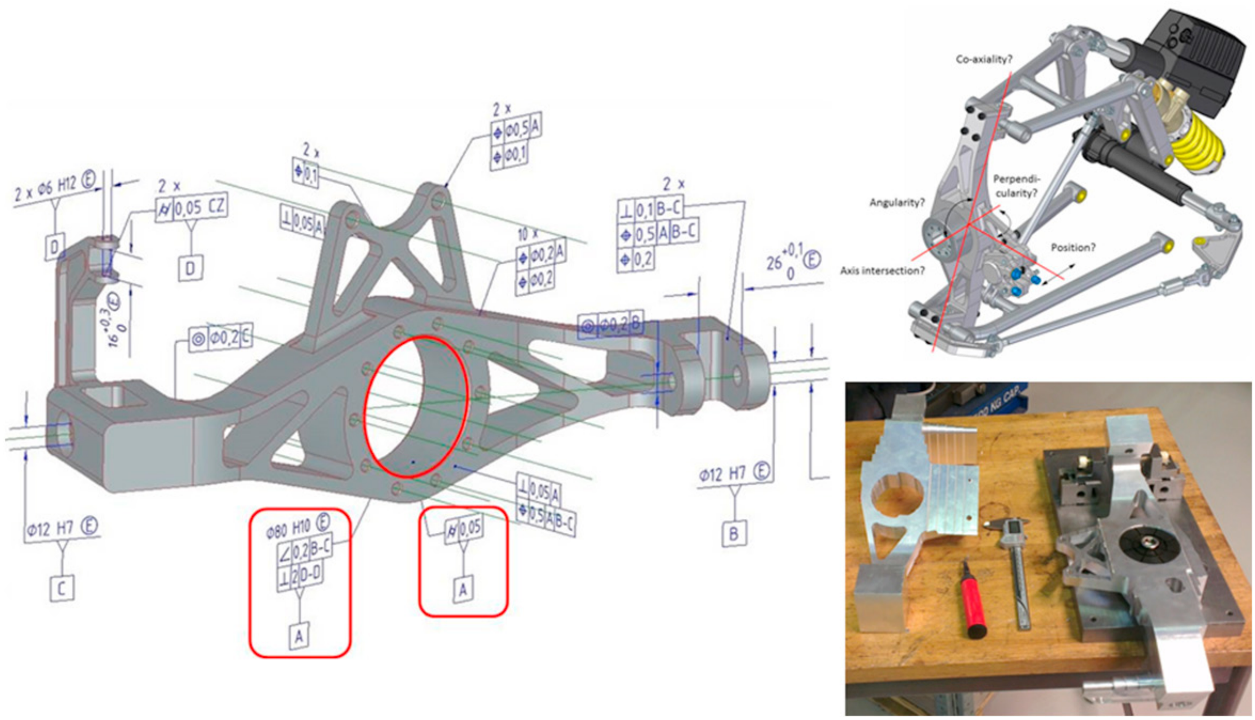

Fig. 1 – Realized function of a large hole of product enabling the purpose of location and clamping

To exemplify: An experienced process planner would likely identify the potential of a large hole of a component (Fig. 1) to be used for location and clamping. Explained more formally; the structure of this artefact in the given physical environment exhibits a behavior which effect a function, interpreted according to human values within a particular socio-cultural environment as enabling a certain purpose to be fulfilled. Rephrasing Rosenman [30], the large hole of the component exhibits the behavior of horizontality and rigidity for a cylinder thus effecting the functions of providing location and orientation of workpiece, enabling the purpose of location and clamping.

5. Design rationale

Design rationale (DR) is an explanation of why an artifact or some part of it is designed the way it is [38]. In an extensive survey of DR systems, Regli [39] explains that capturing and preservation of intellectual capital have been of importance for organizations for a long time. However much of the information is stored in people's memory, desk drawers, etc. Effective DR systems are of interest for companies as they could enable a wide variety of knowledge reuse via; design decisions and their rationale, justifications and other design alternatives, trade-offs, etc. Capturing of design knowledge must be managed with minimal overhead, without disturbing the natural progression of design activities, and without shifting the focus of designers' work from creative design tasks to more tedious documentation tasks. Hence, an effective DR system would facilitate generation, storage and retrieval of design information associated with the designed artifact and its design context. Chandraskaran [31] propose functional representation (FR) as a mean to capture DR. The causal components of DR can be represented through a FR scheme in which the overall function of a device and the behavior of each component in the context of this function are described. Encoding the designer's account of the causal processes in the device that culminate in achieving its functions, the scheme can provide a partial DR in the sense as an account of how the designed artifact serves or satisfies expected functionality.

6. Model driven process planning and process design

Digital models are used to various degrees in manufacturing engineering to support synthesis, analysis and communication. Model driven process planning is a methodology emphasizing the application of digital models to create, represent and use information of products, processes and resources. The resulting process plan is a digital and computer interpretable model defining what is to be machined and how by representation of operations, operation sequence, machining features, initial stock, in-process parts, manufacturing resources, etc. Coherent information, a cornerstone in model driven process planning, enables the integration of quality assurance and risk assessment activities as PFMEA in process planning. Employing the international standard ISO 10303-242 Managed model-based 3D engineering (STEP AP242) [41], recently ended research project FFI – MPQP [40] has demonstrated a novel approach where PFMEA elements as; failure mode, failure severity, failure effect, and failure occurrence are represented in context with a product´s process plan that encompass the product geometry, its features, geometrical dimensions and tolerancing (GD&T), etc. Today, design intent is usually not captured and communicated in process planning. Hence the design rationale behind the process becomes obscured for others. To capture and communicate design intent and design rationale in process planning is important as the process planner´s decisions contribute to set the manufacturing conditions for the final product quality. PFMEA elements can, as demonstrated in FFI – MPQP [40], be represented in a STEP AP242 process plan model. As STEP AP242 has no technical constraints that prevent representation of purpose and function of manufacturing operations too, a STEP AP242 process plan model could potentially serve as a partial design rationale similar to as explained by Regli [39] and Chandraskaran [31]. Model driven process planning also enables feed-back of machining and inspection information in context (Fig. 2). Product and manufacturing process design intent, failure modes, causes and effects, as well as real events, measuring values, process data, etc. can be related to features and manufacturing operations, enabling comparison between design objectives (as-planned) and inspection and machining information (as-realized) from which structured knowledge can be developed to improve product and process design. As explained by Hedlind [43], collaborative process planning can be effectively supported by a model-driven approach in which planning can be initiated as soon as a function for a part to be designed is given. During the course of part design, product functions are related to design solutions and manufacturing processes until a design solution has been finalized, enabling the process plan to be finalized. Such approach enables a mutually beneficial cross-disciplinary work where all parties involved can contribute to increased application knowledge and better understanding.

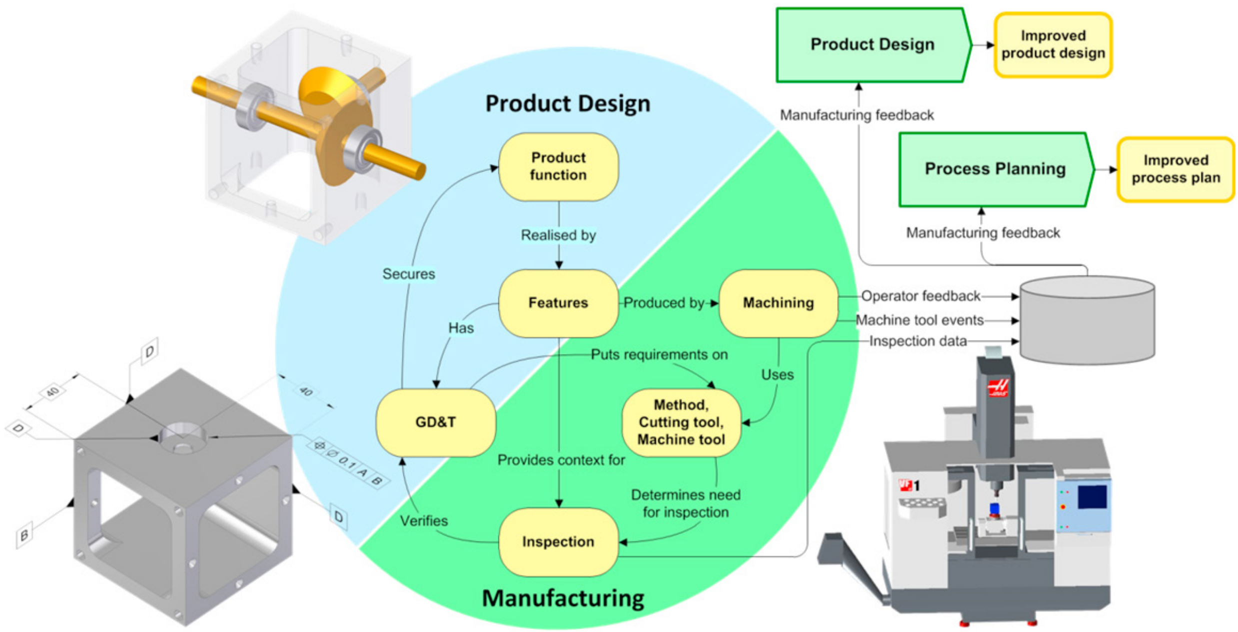

Fig. 2 – Shape, function, context provides engineering meaning of a shape of a product.

7. Conclusion

Human skills are far from being obsolete and humans are by no means a disappearing residual. Human capabilities such as; intelligence, creativity, adaptability, makes skilled humans become primary assets in a modern manufacturing company. Skills which can be exploited more efficiently by CAD/CAM systems utilizing coherent digital models, carrying information created in design and process planning through the product realization process. CAD/CAM software´s should be designed to support human expertise instead of aiming to imitate and replace it, or as concluded by Brödner [20]; Human work should not be seen in terms of failures and costs, but rather as the primary source of productivity. Instead of searching for the potentials of technology and the limits of man, efficient production might require looking for new ways of combining the unique capabilities of humans with the performance of machines.

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