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Human-Centered Model-driven Process and Quality Planning

Magnus Lundgren[a]*, Mikael Hedlind, Yujiang Li, Torsten Kjellberg

[a]*KTH- Production Engineering, Stockholm, Sweden*

* Corresponding author. Tel.: +46-8-7909309; fax: +46-8-210851. E-mail address: brix@kth.se

Abstract

Process and quality planning are prerequisites for the production of qualified products at competitive cost. Today´s document-based work methods are not effective as valuable time is spent on document creation and document management instead of being spent on innovation and process improvements. Information duplication is an inevitable consequence with current document-based work methods where the same information is described in different ways, at many places, across many different documents. This paper presents a model-driven approach where vital manufacturing information is described once, at one place, and in one way, enabling improved work methods for cross-organizational process and quality planning.

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Keywords: Model-driven; Process planning; Quality planning; Process failure mode and effect analysis

1. Introduction

Process planning is a vital link between design and manufacturing for realizing the designer´s intent at competitive cost. Type of products, production rate, annual volumes, company strategies, etc., gives different possibilities and constraints for process planning which, depending on situation, will encompass different activities, strategies and methods [1]. Quality planning is as equally important as process planning as it must be ensured that the determined manufacturing process is capable to produce products that comply with defined requirements.

These two processes are interrelated, but lack of efficient integration as well as lack of effective work methods and media that can represent vital manufacturing information hinders them from being executed in a mutually beneficial concurrent manner. Today´s document-based work methods are very time-consuming as lots of different documents have to be created, managed, and maintained in process planning and quality planning. Lot of the information is common but is described in a fragmented manner across many different documents with information duplication as an inevitable consequence.

2. Process planning

Engineers design products and systems which perform intended functions. Hence, function is a key concept in design, as well as in process planning, where a manufacturing process on a macro-level can be seen as a system, whose function is to transform a blank into a product, where each operation has some purpose in the sense of performing an intended function in the whole.

Planning can in generic sense be viewed as: the activity of devising means to achieve desired goals under given constraints, with limited resources [2]. Means are processes or artefacts which fulfill some function in bringing something to an end [3]. Hence, manufacturing processes are different means, or modes of action by which an operation fulfills its purpose. There are many manufacturing processes to consider in process planning, e.g.; cutting, forming, heat treatment, welding, surface treatment, assembly, etc., which all perform intended functions, but sometimes also performs unintentional functions. Unintentional functions can have positive or negative effects, which in the latter case conceptually is regarded as “side effects” [4] i.e. something which is non-intentional but nevertheless occurs. Applied in process

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planning, a concrete example could be hardening where the intended function is to achieve a microstructural transformation of the workpiece material which increases its strength. However, a well-known inevitable side effect of hardening is shape deformations and residual stresses.

Side effects may have to be considered in process planning where the process planner´s knowledge, experience, and ability to foresee the effects of decisions made during planning, are important factors in defining processes with predictable outcome. Such expertise evolves from experiences obtained through practical work where processes are defined, follow-up is made, and corrective measures are taken during production [5]. By time, and years of practice, ability to identify potential problems in advance enables experienced process planners to design manufacturing processes in a pro-active manner.

Unfortunately, today´s work methods fail to take advantage and exploit the outcome of these valuable considerations in quality planning, as current tools lack effective ways to integrate the reasoning and rationale behind process planning decisions.

3. Quality planning

Quality planning has evolved from past day´s simple part inspection in manufacturing to today´s system engineering approach throughout the product realization process to ensure that all processes and products comply with defined requirements. Quality planning in the automotive industry is based on the principles and requirements outlined in the Advanced Product Quality Planning and Control Plan (APQP) reference manual which provides a structured method of defining and establishing the steps necessary to assure that a product satisfies the customer´s requirements. APQP was released by Chrysler Corporation, Ford Motor Company, and General Motors Corporation in 1994, and current revised 2nd edition was published in 2008 [6]. APQP has been adopted as AS9145 [7] in aerospace industry.

APQP, Statistical Process Control (SPC), Measurement System Analysis (MSA), Failure Mode and Effects Analysis (FMEA) and Production Part Approval Process (PPAP) are referred to as “the Five Core Tools” by the Automotive Industry Action Group (AIAG). These tools are building blocks for quality management in automotive industry, and have been harmonized in ISO/TS 16949:2009 [8] which specifies particular requirements for the application of ISO 9001 [9] for automotive production. The research presented in this paper has focused particularly on improving tools and work methods for the production part approval in automotive industry; hence SPC and MSA will be left out in further discussion.

PPAP [10] is a standardized procedure required to be implemented in companies that are suppliers in automotive industry to ensure that their manufacturing systems are capable of consistently meeting engineering design requirements and specifications. Whenever a new or modified component is introduced to production, or when the manufacturing process is changed, suppliers are required to obtain a PPAP approval from their customer.

PPAP is a series of documents (Fig. 1.) whose purpose is to provide proof that the supplier’s manufacturing process is capable of producing the customer´s product in serial production.

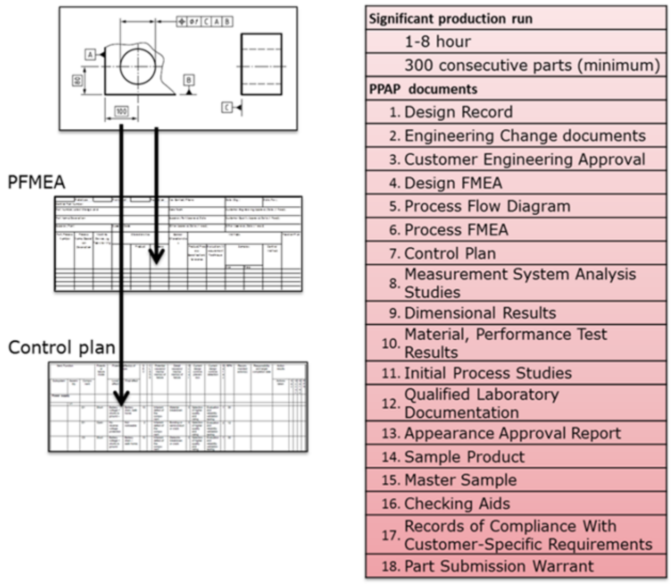

Fig. 1. Today´s document-based Production Part Approval Process (PPAP) where product, process, and quality planning information is presented many times, in many ways, and in many documents.

Risk assessment and risk analysis are emphasized as particularly fundamental activities in ISO 9001 and in PPAP where FMEA and PFMEA are required activities. FMEA, standardized as EN IEC 60812:2018 [11] is a systematic method of identifying and evaluating the ways in which an item or process might fail, and the effects of failure upon the performance of the item or process. In the latter case it is referred to as Process Failure Mode and Effects Analysis (PFMEA). Failure modes are commonly ranked in order of their criticality to enable prioritization of countermeasures. In such cases the analysis is known as Failure Mode, Effects and Criticality Analysis (PFMECA) where one common method to quantitatively determine criticality is by Risk Priority Number (RPN). RPN is a product of the three ratings; severity of the effect, estimated probability of occurrence, and probability of detection.

Findings from research in Swedish automotive manufacturing industry [12] indicate that the companies were spending a lot of time on risk assessment activities where PFMEA is a commonly used method for risk assessment. At the companies, PFMEA was carried out in cross-functional teams consisting of product designers, process planners, manufacturing engineers, machine tool operators, CMM operators and quality engineers, where the teams were lead and coordinated by a PFMEA moderator.

However, it was found that complex organisation structures, task complexity, and lack of efficient tools, contributed to counteracting the efficiency of the work. For instance, a common experience at the studied companies was that the outcome of a PFMEA is highly dependent on the group´s constitution, where the difference between having a skilled PFMEA moderator or not could influence the resulting

PFMEA document and its validity a lot. It was also reported that use of inappropriate tools such as Microsoft Excel could result in large and complex PFMEA spreadsheet documents, requiring substantial manual work. Manufacturing engineers at the companies experienced the outcome of the PFMEA work as low compared to the work effort they have to put in. As a consequence, PFMEA documents may not be revised during regular continuous improvement activities. It was also mentioned that lessons learned in one PFMEA were not easily transferable and possible to implement in other PFMEAs´ due to difficulties to compare and manage failure modes between different PFMEA documents.

4. Research approach

This paper addresses shortcomings of work methods and software for process and quality planning identified in close collaboration with Swedish automotive manufacturing companies [12]. Work methods at the companies have been studied in parallel with examination of software for process and quality planning from companies such as Siemens, Dassault, ReliaSoft, IQS, etc. Manufacturing engineers at the companies have shared their experiences and thoughts in open-minded discussions in cross-organizational workshops.

When comparing industry needs, work methods, and functionality of studied software, a gap was identified in the sense that current mainly document-based work methods in quality planning fail to capitalize on already created information from process planning. Furthermore, lack of software interoperability in process and quality planning results in information fragmentation, data duplication, and possible data inconsistency.

Previous research [13 - 18], performed and demonstrated within the work of ISO/TC 184/SC4/WG 15 - Digital Manufacturing, has demonstrated the feasibility of a model-driven approach in manufacturing. Hence the research thesis of this paper is that the application of a model-driven approach for process and quality planning can contribute to bridge the gap mentioned above.

In close collaboration with manufacturing engineers from automotive companies, functional requirements in terms of representation and presentation of relevant process and quality planning information, as well as relevance of attribute data, and design of a case scenario for demonstration of model-driven process and quality planning, were discussed and evaluated. Based upon this collaboration, a prototype software for demonstration of integrated model-driven process and quality planning, utilizing international standards for product model data representation such as ISO 10303-238 (STEP-NC) [19], ISO 13399 [20], and ISO 10303-242 (AP242) [21] was developed.

5. Model-driven Process and Quality Planning

Model-driven process planning is a methodology that emphasizes the application of digital models to create, represent and use information about 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 final part, initial stock, manufacturing features, machining operations and operation sequence, intermediate in-process shapes, manufacturing resources such as machine tools, fixtures, cutting tools, etc. Model-driven process planning is a human-centered approach in the sense that its objective is not to imitate or replace human process planners but to enable them to exploit their expertise more efficiently by providing CAx software designed to support human capabilities as; intelligence, creativity, and adaptability.

As mentioned in the introduction, information duplication is as an inevitable consequence of current document-based way of working. A model-driven approach can contribute to reduce waste in form of re-creation of existing information as coherent digital models enables the information to be described once, at one place, and in one way. The model-driven approach for process and quality planning presented in this paper uses the international standard AP242 for representation of PFMEA elements such as failure modes, failure effects, and failure occurrence, in context of a Process Plan´s manufacturing operations.

ISO 10303 STEP (STandard for the Exchange of Product data), is an widely used system neutral solution for industrial data representation, implemented in most major CAx systems for exchange of 3D geometry data. Through the common information modeling language ISO 10303-11 EXPRESS [22] standards such as STEP NC and AP242 can be integrated to share information with each other, and with other international standards, such as ISO 13399, which also are using the EXPRESS language as its implementation method.

The result presented in this paper is an additional and important contribution in achieving effective digital manufacturing, facilitating a complete and seamless product data exchange cycle throughout the product realization process.

6. Case scenario

For the demonstration of model-driven process and quality planning, the machining of a gear box housing (Fig. 2.) was

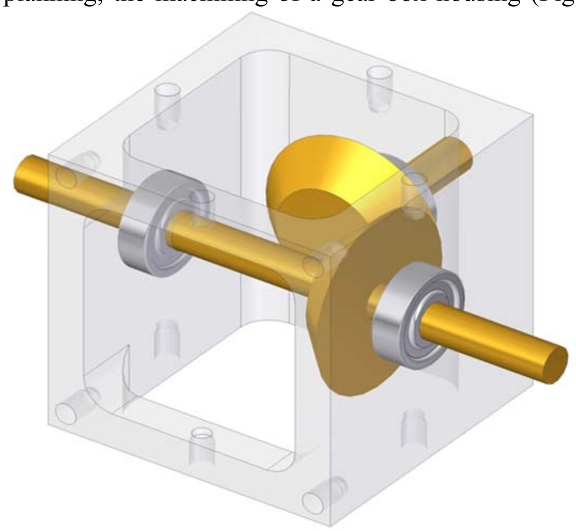

Fig. 2. Case scenario product, a gear box housing

decided as a case scenario. The gear box housing, developed at KTH Production Engineering, has been used as a test case on several occasions within ISO/TC 184/SC4/WG 15 - Digital Manufacturing.

One thing which attracts a process planner´s attention is the mutual functional relationship between the center-axes of the three bearing seats which is a strictly axis to axis locating tolerance relationship [23] implying that machining of the bearing seats is preferable done in the same setup. Hence a four, or a five-axis milling machine would likely be a process planner´s primary choice for the machining of the gear box housing. Possible deformation of the rather weak final structure of the gear box housing must also be considered in setup planning as the gear box housing might become deformed during clamping.

As the intention of the case scenario is to demonstrate management of PFMEA and Control Plan information throughout multiple stages of a manufacturing process, the process planning scenario was intentionally decided as alternative machining in a second choice, three-axis machine due to unavailability of a more versatile five-axis machine, which, as already mentioned, otherwise would have been a process planner´s first choice for a product like the gear box housing.

One important consequence of the decision to use a three-axis machine instead of a five-axis machine is that the three bearing seats will be machined in different setups. Hence, the decided three-axis approach is significantly riskier and is more likely to fail as every setup is a potential source of errors and deviations.

Even though it would have been possible to machine the gear box housing in six setups, a seven setup approach have intentionally been decided as illustrated in Fig. 3. The rationale behind this decision is to maintain the structure as rigid as possible, while machining the critical features of the gear box housing; the three bearing seats.

6.1. Setup 1 – Create process function

In setup 1 the top face is machined and a step around the workpiece is created. As the step has no function from a product point of view the rationale behind it might be questioned. However, the step fulfills an important process function in serving as intermediate location surfaces in setup 2, 3 and 4. The rationale behind the step is to improve the location conditions for the machining of the three bearing seats.

6.2. Setup 2

In setup 2 the top face (indicated by red in Fig.3.) from setup 1 is put against the solid jaw of the vise with one the four surfaces of the step resting on a single parallel at the bottom of the vise.

6.3. Setup 3, 4, and 5 – The critical setups

For setup 3, 4, and 5, the top surface from setup 1 is kept against the solid jaw of the vise while the workpiece is rotated 90 degrees between each setup. The step does not provide any function after setup 4, and it is completely removed in setup 5.

6.4. Setup 6 and 7

In the two last setups the internal material of the workpiece is removed. To avoid unnecessary long overhang of the cutting tool, the internal material is removed from two directions. There is no machining of the top surface in setup 7 which was machined in setup 1 (indicated by red in Fig.3.). As explained, the rationale behind not removing any internal material in setup 1 was to maintain the structure as rigid as possible for the critical setups.

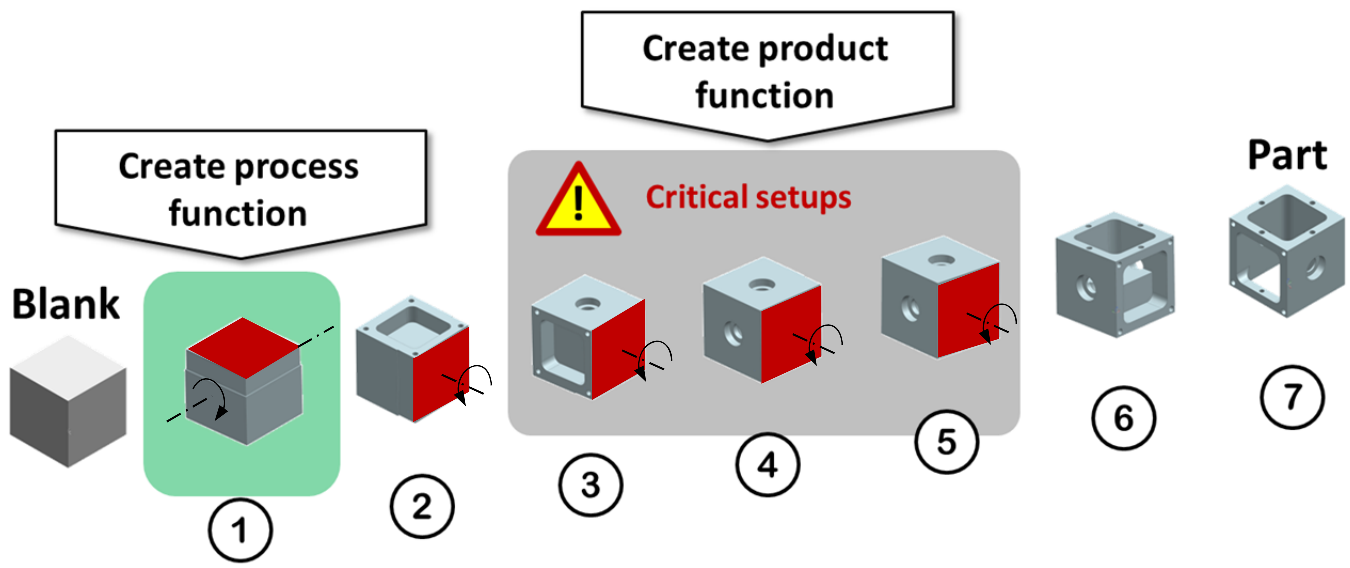

Fig. 3. Process Plan layout for machining of the gear box housing in a 3-axis machine

7. Case demonstration

To demonstrate model-driven process and quality planning, KTH Production Engineering developed a JAVA-based STEP viewer where PFMEA and Control Plan information is presented in the context of a Process Plan. A digital AP242 Process Plan model for the gear box housing was modelled in AGREE, a software developed at KTH Production Engineering, enabling users to create STEP instance diagrams via a graphical interface.

The digital Process Plan model contains the operations, aka. workingsteps, for the machining of the gear box housing, organized in setups, as well as 3D models of the initial blank, the final product, and every intermediate in-process shape product for the setups 1 – 6. Also, fixtures, cuttings tools, and measurement devices such as a Vernier caliper and a Renishaw touch probe are represented as 3D models in the digital AP242 Process Plan model.

The 3D models were created in Siemens NX 11 and exported as AP242 product models with associated Product Manufacturing Information (PMI), consistent with the International standard; ISO 17450 - Geometrical product specifications (GPS) [24]. AGREE was used for the integration of the 3D models in the AP242 Process Plan, as well as for the modelling of PFMEA elements and Control Plan information.

The AP242 Process Plan for the gear box housing can be opened in the KTH STEP viewer, enabling a user to browse the Process Plan with its related PFMEA and Control Plan information. In the screenshot of the KTH STEP Viewer (Fig. 4.) a failure mode; out of tolerance, with Risk Priority Number (RPN) 25, has been selected. A user can investigate which setup and workingstep the particular failure mode belongs to by expanding the failure mode node. The user can also investigate the failure effects and failure causes of a certain failure mode. Related features are highlighted in the 3D model on the screen. Full traceability of where (and how) a certain product characteristic is realized, is possible as every product characteristic of the Control Plan is related to the workingstep in which it is created.

8. Conclusion

The model-driven approach presented in this paper can potentially reduce non-value adding re-creation of existing data, enabling engineering competence to be used for process improvements and innovation, instead of being spent on document creation, maintenance and management.

The possibilities for a digital Process Plan model to serve as a single source for different kinds of manufacturing instructions have been demonstrated in [14]. As presented in this paper, a digital Process Plan model can also serve as a single source in integrated process and quality planning. In principal, the digital Process Plan model is by itself a very versatile information base, which enables users to only see information relevant to their needs through the use of different model views. The response from manufacturing engineers has been very positive when the KTH STEP viewer with the

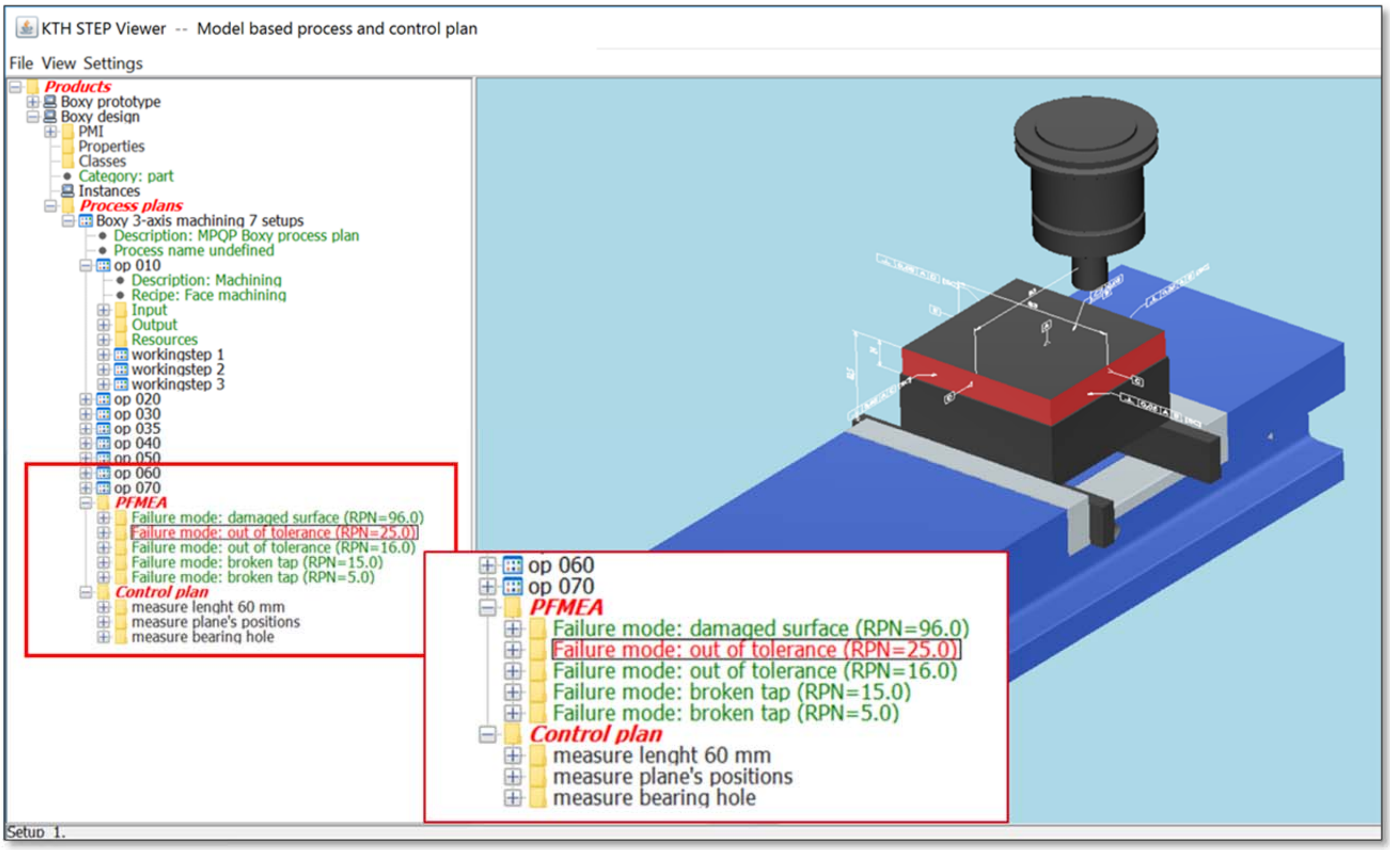

Fig. 4. AP242 Process Plan, with integrated PFMEA and Control Plan information for the gear box housing. By expanding a failure mode node the relationship to the workingsteps of the process plan can be investigated, where related features of the product model are highlighted on the screen.

AP242 Process Plan for the gear box housing has been presented in industry. The response within ISO/TC 184/SC4/WG 15 - Digital Manufacturing, has been very positive too, where for instance, Larry Maggiano, Senior Systems Analyst at Mitutoyo America Corporation, after a demonstration in December 2017 said that:

"*Today's presentation in the STEP Manufacturing web conference on Model driven Process and Quality Planning (MPQP) was very enlightening. Moving to a model-based PPAP that includes an integrated model based implementation of a PFMEA and a Control Plan addresses (at least to us) a critical segment of the MBD workflow.*"

As discussed by Lundgren et al. [25], a AP242 Process Plan model can potentially also serve as a partial design rationale, where feed-back of events, process- and inspection data, etc. is done in the context of the Process Plan, enabling comparison between design objectives (as-planned) and inspection and machining information (as-realized), from which knowledge contributing to improve products and manufacturing processes can be developed.

The potential for model-driven process and quality planning as discussed and presented in this paper is large. However, there is a gap to bridge in manufacturing research, where a current main barrier for implementation of a model-driven approach as presented in this paper is lack of CAPP software capable of generating digital Process Plan models such as the one demonstrated in the KTH STEP viewer. Further research in model-driven manufacturing is therefore motivated.

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