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Model Driven Manufacturing Process Design and Managing Quality

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Abstract

Besides decisions in design, decisions made in process planning determine the conditions for manufacturing the right quality. Hence systematic process planning is a key enabler for robust product realization from design through manufacturing. Current work methods for process planning and quality assurance lack efficient system integration. As a consequence companies spend unnecessary lot of non-value adding time on managing quality. This paper presents a novel model-based approach to integrate process planning and quality assurance. The presented model enables a more efficient and holistic way for managing quality from design to manufacturing. New possibilities to communicate process design intent and present important quality assurance information in a more structured and comprehensive way is also enabled.

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Keywords: Model-driven; Process planning; Process design; Process Rationale; Quality assurance

1. Introduction

In the well-known novel by Lewis Carroll [1], the following dialogue takes place between the main character Alice and the Cheshire cat when Alice asks the cat about which way to go;

> *'Would you tell me, please, which way I ought to walk from here?'*
> *'That depends a good deal on where you want to get to,' said the Cat.*
> *'I don't much care where —' said Alice.*
> *'Then it doesn't matter which way you walk,' said the Cat.*

The same is true for process planning which definitely is a matter of making decisions on how one ought to convert the designers' idea into a physical product. The overall aim of process planning is to design a robust manufacturing process capable of producing components of right quality at a competitive cost.

Product quality does not only depend on control activities and downstream inspection in the manufacturing process. The decisions made in product design and in process planning determine the conditions for manufacturing the right quality.

Every manufacturing process and operation must be designed in the best possible way. Each process step shall contribute and ensure that the overall process chain leads to the right product quality.

1.1. *Manufacturing process design*

Process planning is definitely more than the term itself might indicate. It includes both creativity, where ideas or solutions are synthesized, and analysis where decisions must be made by evaluation of proposed ideas. The analytical activities, such as comparing and evaluating different alternatives, have been thoroughly studied by [2, 3, 4, 5, 6, 7, 8, 9] to mention a few. Several thousand publications about process planning have been published but few have studied the creative part of process planning. In a paper [10] about a solution for model-based interactive learning of process planning in master level production engineering courses, Lundgren et al. mention that 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.

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To emphasize that process planning includes both creativity and analysis we use the term "process design" to refer to the activity whose outcome is the process plan.

The creative part of process design is subjective, and depends on the process planner´s expertise, knowledge base and creativity. For the same set of requirements, virtually an infinite number of possible solutions can be created. Since the process planner must be able to abandon or discard bad ideas quickly to enable the creation of new ideas by exploring different possibilities etc., creativity and analysis are inter-related in process design.

The outcome, i.e. the process plan, is mostly represented in different kind of documents. Usually, these documents only communicate what to do and leave out the important manufacturing process design intent. As process design reasons are not expressed in a clear and explicit way the rationale behind the decisions and why they were made becomes hidden for others.

Communication of design rationale in product design has been discussed by Price et al. [11]. However, besides the work presented by Lundgren et al. [12], process design rationale have not been thoroughly discussed in current process planning research.

Being able to communicate process design intent, i.e. the reasoning behind the decisions and why they were made, in an efficient way would be valuable in process plan evaluation and quality assurance activities.

1.2. *Quality assurance in manufacturing industry*

Quality assurance in production is as important for robust product realization as effective process planning. The purpose of quality assurance is to ensure that processes and products comply with defined requirements. Historically, quality assurance has evolved from a focus on part inspection of manufactured products to a more holistic approach where quality assurance is an integrated activity throughout the whole product realization process.

Colledanio et al. emphasizes that the mutual relations among quality, production planning and maintenance control should not be underestimated. They propose "Production Quality" as a new paradigm aiming at going beyond traditional six-sigma approaches. Innovative and integrated quality, production logistics and maintenance design, management and control methods as well as advanced technological enablers have a key role to achieve the overall "Production Quality" goal [13]

1.3. *Management and analysis of risks in manufacturing*

Today, manufacturing engineers are using different CAx applications for process planning and quality assurance. For process planning CAM is widely used, mainly for creating and verifying toolpaths for CNC machine tools. For quality assurance other types of software is used. Available software applications to support quality assurance activities as process Process Failure Mode and Effect Analysis (PFMEA), Measurement System Analysis, and creation of Control plans etc. can be categorized as PLM software as solutions from PTC, Dassault Systémes, Siemens PLM and ARAS, or CAQ software as from Q-DAS, Babtec, Boehme-weihs, IQS. In addition, a common solution is to build on desktop applications such as MS Office (Word, Excel etc.). Regardless of software category, they share the problem of effective information integration between process planning and quality assurance.

Careful planning in an early phase is emphasized in the Advanced Product Quality Planning and Control Plan (APQP) reference manual. It was first issued by Chrysler Corporation, Ford Motor Company, and General Motors Corporation in 1994 and in 2008 a revised 2nd edition was published [14].

The importance of the principles in the APQP reference manual is indisputable. But the task of creating and managing APQP required documents such as a PFMEA, results in high workload. Furthermore, the creation of them is almost exclusively done in a document-centered approach, separated from the process planning activity.

One of the main objectives with process planning is to define a process with a predictable outcome. Hence, the decisions made during process planning contribute to a large extent to set the manufacturing conditions for the final product quality. Bagge suggests in his Doctoral thesis that risk assessment activities as PFMEA should be an integrated activity in process planning [15]. But lack of efficient system integration between process planning and quality assurance make it difficult to fully exploit valuable information in the process plan.

The way a process planner design the process plan depends a lot on the process planner´s ability to identify and address potential problems in advance. Experienced process planners can prevent problems from occur in manufacturing by designing the manufacturing process in a pro-active way. Process plan information such as; process step, process sequence, manufacturing resources, etc. is important in quality assurance activities as PFMEA. But there is very limited, if any, integration at all between process planning applications, e.g. CAPP/CAM and quality assurance applications. As a consequence, manufacturing companies fail to exploit valuable data created in process planning when working with quality assurance.

Besides failing to exploit valuable information created in process planning, today's quality assurance work methods result in unnecessary waste of manufacturing engineer expertise. As the required quality assurance documentation in many cases is created by process planners, their competence is used in an inefficient way when they re-create information already created in process planning. Instead of doing the documentation the focus should be on improving production contributing to create customer value.

1.4. *Model-driven process planning*

While process planning and quality assurance today is performed in a disconnected manner, there is a huge potential in applying a model-driven approach. Model-driven process planning is a methodology that emphasizes the application of digital models to create, represent and use information of products, processes and resources. The objective is to support

skilled process planners by using computer software for information utilization through modeling in communication, creation, visualization and interaction.

Coherent information is a cornerstone in model driven process planning where the resulting process plan is a digital and computer interpretable model defining what is to be machined and how to machine the product by representation of operations, operation sequence, machining features, initial stock, in-process shapes, manufacturing resources, etc.

With reference to von Euler-Chelpin [16], Hedlind discuss how digital models can be utilized in collaborative production engineering by carrying information about and relationships between the product, its functions and its manufacturing processes [17].

Not only Geometric Dimensions and Tolerances (GD&T), machining features and machining operations can be represented in a digital model. Also PFMEA elements, such as failure modes, failure effects, failure occurrence, etc. can be represented. Moreover, it is possible to represent *Special characteristics*, a key concept in the APQP Reference manual and in ISO/TS 16949:2009 [18], in a digital model and to specify the relationship between the *Special characteristics* of a product and process plan elements such as the GD&T for a certain feature, datum surfaces, and more.

2. Research approach

An underlying premise for the research presented in this paper is that a process plan is a detailed manufacturing solution from a process design intent, and that process planning is performed based on a process design rationale, i.e. a logical reasoning as a basis for a process planner in making decisions.

The thesis of this paper is that new and radically improved work methodologies can be realized through utilization of coherent digital models, which carries information generated in product design, process design and manufacturing, throughout the whole product realization process, enabling a holistic approach in which process planning and quality assurance are performed in an integrated way.

By capturing and process design information in digital models and reuse it effectively in quality assurance, waste in form of re-creating already created information will be drastically reduced.

2.1. *Research case study*

Risk assessment is important in both design and in manufacturing. The latest revision of ISO 9001 [19] particularly emphasizes structured risk assessment as a fundamental activity. To ensure that a supplier´s manufacturing system is capable to consistently meet engineering design requirements and specifications, the Automotive Industry Action Group (AIAG) has defined the Production Part Approval Process (PPAP) [20] as a standard required to be implemented in companies that are suppliers in automotive industry. Methods and tools used for quality assurance, e.g. PFMEA have been harmonized in ISO/TS 16949 in which the PPAP is included.

PFMEA is regarded as an important quality assurance activity and it is required for suppliers in automotive industry. It is a step-by-step procedure to evaluate risks of failure in a manufacturing process. The aim is to identify potential failures, the severity of the failures, and the effect of the failures. It is common that failure modes in a PFMEA are ranked by combining the severity measure, frequency of occurrence, and possibility for detection, to produce a metric called criticality. One method to quantitatively determine criticality is the Risk Priority Number, RPN. It is a means of ranking the severity of the failure modes to allow prioritization of countermeasures. Risk is here evaluated by a subjective measure of the severity of the effect, estimated probability of its occurrence, and possibility for detection.

Studies conducted in the Swedish national research project FFI - Model-driven Process and Quality planning (MPQP) [21] has shown that Swedish automotive manufacturing companies spend lot of time on performing PFMEA.

At the studied companies the PFMEA is commonly done by a cross-functional team where typical participants are; product designers, process planners, manufacturing engineers/technicians, machine tool operators, CMM operators and quality engineers. The work is lead and coordinated by a PFMEA moderator. The outcome of the PFMEA work is highly dependent on the group. A skilled moderator can make a big difference on the result and its validity in quality assurance.

During several meetings over time the manufacturing process in analyzed by the PFMEA team which, from the very first to the last manufacturing operation, step by step try to identify potential failure modes in the manufacturing process. The resulting PFMEA document, usually a spreadsheet, can be quite large. In some cases a PFMEA can consists of several thousand rows distributed over many tabs in the spreadsheet.

It is difficult to identify and focus on the most relevant risks. A team might focus on risks which not are so relevant but fail to identify more relevant risks. It is difficult to define an appropriate breakdown of the process, and to determine a feasible level of detail in the PFMEA. Lack of proper tools and complexity of task usually leads to heavy manual work.

Due to the nature of PFMEA it is difficult to detect and manage relationships between similar products and manufacturing processes. Due to complex organization structures and lack of time, the inter-disciplinary and cross-organizational work emphasized in APQP, is not performed as efficient as supposed.

PFMEA is many times done to late in product development. If a design problem is identified during the PFMEA work, there are usually few possibilities to adapt the product design. Manufacturing companies experience that the outcome of PFMEA is low compared with the effort they put in, and that the result is not used in an efficient way. For instance, due to the big work effort PFMEA is not revised during regular continuous improvement activities. There is also lack of efficient feed-back, e.g. if there is a customer complain the PFMEA is necessarily not updated.

3. Research results

The research presented in this paper is based on several years of work with information modeling for process planning, performed in national Swedish research programs [22, 23, 24] in close collaboration with Swedish automotive manufacturing companies such as Scania and Volvo, and in international collaboration within the International Organization for Standardization, Technical Committee 184, Sub-committee 4 (ISO TC184/SC4).

The motivation for PFMEA as a quality assurance activity in automotive manufacturing and other industries is undisputable but current commonly spreadsheet-based approach is not effective. The companies in our case study share similar experiences of PFMEA, namely that the outcome of the PFMEA is low compared with the effort they put in to it. They think current spreadsheet-based approach makes it difficult to compare different PFMEAs with each other, i.e. it is difficult to apply, and reuse results from one PFMEA in another PFMEA. The spreadsheet-based approach also makes it difficult to identify product and manufacturing process similarities and to manage such relationships.

Current work methods and tools for quality assurance fail to exploit valuable data created in process planning. When already created information from process design have to be re-created in quality assurance activities as PFMEA, information manufacturing engineers' competence is not used in an inefficient way.

In this paper we propose a novel model driven approach for manufacturing process design and managing quality. The proposed approach has potential to overcome most of above mentioned shortcomings with today´s work with PFMEA for quality assurance.

Increased usage of various kinds of software for process planning and virtual manufacturing, need for interoperability between different CAx applications in product realization, the inter-disciplinary and cross-organizational work which is emphasized in APQP, and the need for being able to collaborate in supply chains, are all strong motivations to advocate a system neutral data representation.

The international standard, ISO 10303 STEP (STandard for the Exchange of Product model data) has been identified as an important technology to enable model-driven process planning. The standard is an important system neutral solution for industrial data representation. Through a common information modelling language ISO 10303-11 (EXPRESS) STEP Application Protocols (AP) as ISO 10303-238 Application interpreted model for computerized numerical controllers (STEP NC), and recently developed ISO 10303-242 Managed model-based 3D engineering (STEP AP242) can be integrated to share information with each other and with several other international standards for manufacturing engineering, such as ISO 13399 for cutting tool representation and ISO 13584 PLib. EXPRESS enable them and other standards which are using the EXPRESS language to share the same implementation methods. Besides having ability to represent products and product geometry, features and GD&T, also manufacturing resources such as machine tools, cutting tools, fixtures etc. can all be represented. STEP also enables integration of engineering concepts with elements of shape and motion together with manufacturing operations and in-process shape models. PFMEA concepts such as failure modes, failure severity, failure effect, possibility for failure detection, etc. can be represented too with STEP.

Feature is a key concept in model-driven process planning. A feature is a prominent or conspicuous part or a characteristic property of "something", an outstanding or marked property that attracts attention. The originally meaning (Latin *factura*, from *facere* "to make) is related to shape or form and the activity of creating, shaping or forming something into a desired shape. But context defines what is characteristic, outstanding or distinctive.

For instance, a design feature may sometimes be similar with a manufacturing feature but not always. The interpretation of a shape from a manufacturing point of view is related to the question; how can we manufacture this shape and what type of process is suitable for that? The interpretation from a design point of view is much more related to the question; what function does this shape fulfill and how to model its geometry?

But as well as features can have product related functions they can also have process related functions. For instance, a face feature or the surface of a hole feature can serve as a datum feature in clamping, i.e. they have a process related function. Such information can be utilized for setup planning, as presented by Stampfer [25].

To decide if a certain feature should be used as a datum for clamping or not, is usually not a decision for the product designer, it is a process planning decision. And in process planning every operation has some purpose. There is an intention behind them. It might be to create a functional surface on the product, as well as to create a process related function, e.g. a datum surface, or to create suitable stock conditions for a finishing operation.

The intention behind a process planning decision can be (but is usually not) explicitly expressed and communicated. Process design intent explains how the process planner has thought to secure product functionality as specified by product design during the design of the manufacturing process.

From this perspective, failure modes represent real experienced or hypothetical ways in which a manufacturing process could fail to deliver products according to the manufacturing specification, or as an expert process planner at one of the companies in our case study expressed it; "*Risk management is basically about answering the question, what can possibly go wrong?*"

From such a viewpoint, failure modes can be regarded as potential obstacles which in some way, through preventive actions must be avoided, overcome or eliminated.

The common spreadsheet-based approach is not suitable, or more correctly expressed, inappropriate for describe the relationship between product, manufacturing process and process rationale in an efficient way. We have choose to use an object-oriented way to model process steps, product- and process functions, process rationale etc. and the relationships to failure modes, failures and failure effects.

In model-driven process planning features are shape representations of engineering requirements. The functional requirements of the product are realized by features. GD&T is used to communicate engineering and manufacturing requirements. Hence, the specified GD&T contributes to secure the functional requirements. If a product and its features are within specified tolerances the product is assumed to function as intended. When inspection and machining data is related to a feature the data will have a clear context from which structured knowledge can be developed. If a failure appears, the failure and the event that caused the failure can be related to a particular feature. The kind of contextualized feed-back data described here will be an important input to develop a digitally represented knowledgebase for improving the design of products as well as the design of manufacturing processes.

The proposed model-based approach, conceptually described in Fig 1, enables structured management of concepts as Process rationale, Product and Process function and Process design in context with features, manufacturing process steps, manufacturing resources, etc.

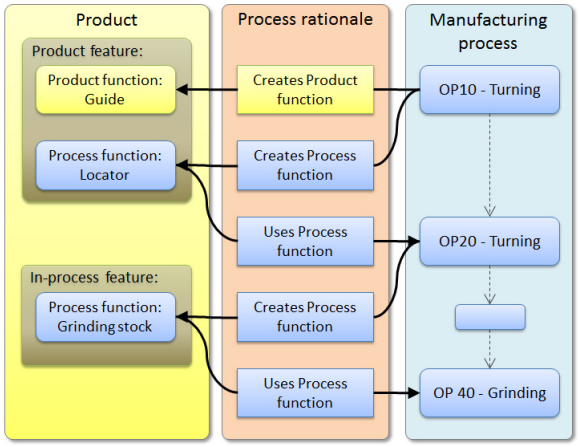

Fig. 1. Model-based process rationale representation integrating product and manufacturing process

Process design intent is the expected manufacturing capability which the planned process have been designed to deliver in the anticipated manufacturing environment.

The process rationale describes the objective with a particular manufacturing process step, e.g. to create a process function, a product function, or both. The objective of a manufacturing process step might in turn be a pre-requisite for other succeeding manufacturing process step which necessary not are executed in direct sequence after each other.

If a manufacturing process step fails to fulfil its expected objective there is a risk that one or several succeeding manufacturing step also will fail. For example, in Fig. 1 manufacturing process step **OP 10 – Turning** creates a product function and a process function. The created process function is then used as locating surface for clamping in manufacturing process step **OP 20 – Turning**. Here, in this manufacturing process step, the objective is to create a sufficiently large stock amount for grinding. Grinding, **OP 40 - Grinding** is not executed in direct sequence with the previous described manufacturing process step.

In the presented model, failure modes are regarded as potential obstacles which possible will result in loss of either a product function or a process function. E.g. if manufacturing process step **OP 20 - Turning** fails to create a sufficiently large stock amount for grinding, then the last manufacturing process step **OP 40 – Grinding** might fail due to lack of sufficient stock amount for a successful grinding.

The proposed model-based approach allows for integration between process planning, and quality assurance applications where information created in process planning is reused in quality assurance without the need for re-enter it. Failure modes, failures and failure effects, are modelled in a context of features, manufacturing resources, manufacturing process steps. Hence, the relationships between failure, failure mode, failure effect and root causes will be significantly easier to manage and keep track of.

4. Conclusions

The presented model-based approach for integrated process planning and quality assurance will enable new functionalities and provide more efficient support to production engineering processes.

The proposed model-based approach for modelling failure modes, failures, and failure effects integrates elements representing product- as well as process functions, and failure preventive actions. Thus it will enable new possibilities to present potential failure modes in a more holistic context and to present important information in a more comprehensive way.

One possible application is for instance Change Point Management. When there is a shift of product in the workshop, in a line, or a cell, operators can be notified about particularly critical characteristics of the manufacturing process, thus know when and where they have to pay extra attention in order to secure realization of products according to customer specification.

STEP AP242 and STEP-NC with needed extensions for supporting quality assurance have the potential to be the main information representation for model driven process planning and quality control to realize new quality assurance work methods that exploits the valuable approved information already created in product design and process planning.

Thereby the proposed model-based approach presented in this paper is expected to have a high potential to contribute to reduce non-value adding re-entering of already created data.

The presented research is an important contribution to the development of the international standard ISO 10303 STEP and other related standards for managing information in digital manufacturing for high quality manufacturing.

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