Product-Process Modelling as an Enabler of Manufacturing Changeability

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Abstract. Today's competitive environment demands increased product variety, more rapid product introductions and increasingly efficient operations in manufacturing. Changeable manufacturing, encompassing reconfigurability and flexibility, provides a mechanisms for addressing these new demands, however there is a significant gap between the concept of changeable manufacturing, and what is actually enabled through operational methods. This paper analyzes how integrated modelling of products and processes can be applied when designing, managing, and operating changeable manufacturing systems. This is structured using generic changeability classes and generic changeability enablers. It is concluded that integrated product-process modelling has a potential to support changeability, especially within the classes reconfigurability, flexibility and transformability. However a theory-practice gap still exists, calling for more research on specific methods and feasibility of such approach

1 Introduction

The markets of today are characterized by an increased demand for product variety, serving both smaller niche markets, as well as individual customers, where products are manufactured to each individual customers' requirements in the business strategy Mass Customization. This implies that many manufacturers face an increased product variety induced complexity that needs to be handled efficiently in their manufacturing systems.

Product life cycles are also continuously getting shorter, as competition drives more frequent product releases. This implies that manufacturing systems, if dedicated to specific products, will have shorter life cycles as well. If manufacturing systems are not dedicated, they will need to be changed more frequently to adapt to new product generations. Worst case, different generations of products need to be manufactured at the same time, increasing the complexity even more. Combining the increased product variety with the reduced product life cycles implies a significant increase in the number of changes in manufacturing systems necessary to remain competitive. The level of complexity and amount of change depends on the product and industry, but this trend is considered general across industries.

Many different approaches have been proposed to deal with these challenges. Within the area of Mass Customization, it is suggested that the development within three capabilities ensures a successful handling of this complexity [12]. These capabilities include 1) choice navigation – helping customers find or configure the right product, 2) solution space development – designing product families which efficiently are able to match the customers' demand for variety, and 3) robust process design – the capability to establish business processes and manufacturing processes which can efficiently handle product variety. Salvador et al. suggest three mechanisms to achieve robust process design: Adaptive human capital, Flexible automation, and process modularity [12], although they do not go deeper into detail on how this can be implemented.

Koren [9] proposed the reconfigurable manufacturing system as a means to achieve a system with a sufficient ability to change, in order to address the above challenges. Although reconfigurability is an important enabler of creating robust process design, recent research suggests that companies must consider more diverse types of changeability, reconfigurability being only one of more types [8]. Wiendahl et al. [13] introduced five different classes of changeability, based on the type and significance of change in the product characteristics and market demand: Changeover ability, Flexibility, Reconfigurability, Transformability, and agility. Below, these concepts will be elaborated.

A significant stream of literature focuses on the design of changeable manufacturing systems [3], [4]. Several publications report that designing manufacturing systems for changeability does indeed have the potential to increase competitiveness [2], [5], [11], however there still seems to be a gap between the potential in applying research results and what is actually being applied in industry.

One common theme across the different publications on how to achieve a changeable manufacturing system, is a coordination between the product domain and the manufacturing domain, referred to by some as co-development or co-evolution [7]. This implies that when making decisions in product development, these must be coordinated with the development of the manufacturing system and vice versa. Doing this, however requires knowledge about the relations between products and processes. This may be achieved by introducing formal models representing both the product variety and the variety of manufacturing processes, from here referred to as product-process models [6]. It is obvious that a model representing product variety and characteristics, and at the same time the manufacturing systems and their relations is useful for co-developing products and correspondingly changeable manufacturing systems. However, current literature does not present any insight into how and by which mechanisms product-process models may contribute to the changeability of a manufacturing system. This leads to the research question of this paper:

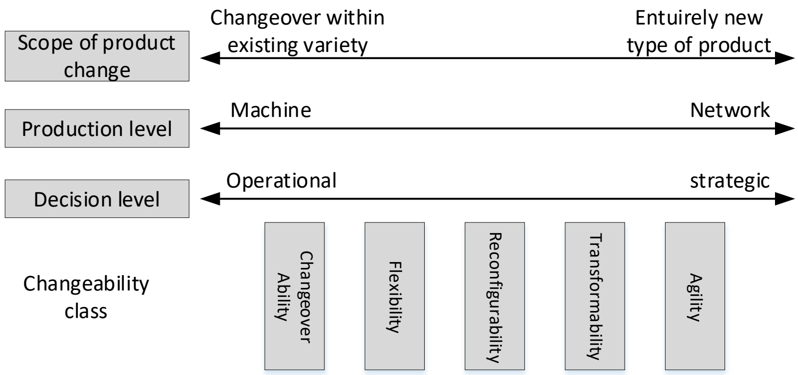
How may an integrated product-process model contribute to increasing the changeability of a manufacturing system?

This research question is addressed by analyzing each changeability class, as outlined below and assessing this mechanisms in product-process modelling can support this specific class of changeability.

1.1 Changeability classes

The remainder of the paper will address the changeability classes from Wiendahl [13] one by one, analyzing which mechanisms provided by product-process modelling may help companies increase manufacturing system changeability. Figure 1 outlines the different changeability classes and their relations to different scopes of product change, production levels and decision levels, as suggested by Wiendahl et al. [13]. The changeability class "Agility", concerns major changes to an entire company implying pursuit of entirely new markets, new products and new manufacturing systems, and is considered out of scope of what is meaningful to address using models of existing products and processes. Hence this changeability class is not addressed further in this paper. Fig. 1 outlines the different changeability classes and

Fig. 1. Changeability classes and relations to product change, production levels and decision levels



1.2 Product-Process Modelling

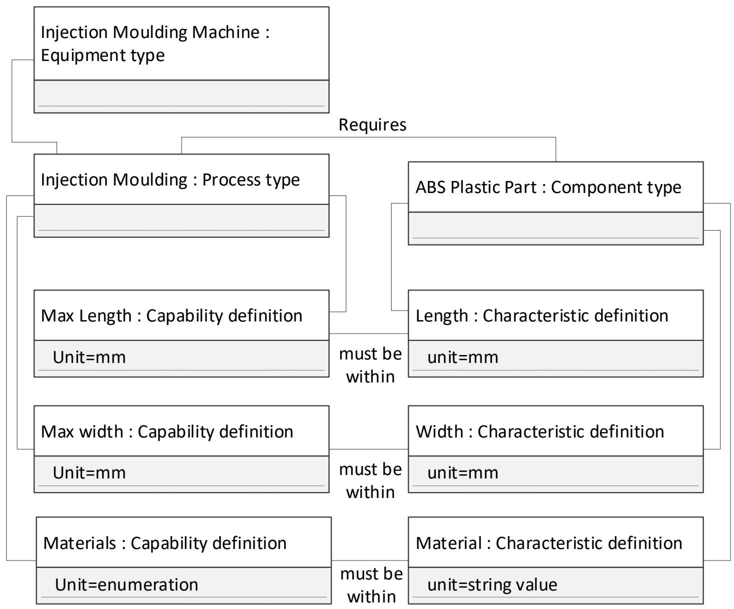
The basic purpose of product-process modelling is establishing a models, which describe products, components, characteristics and variety, while also describing manufacturing systems in terms of equipment, processes and process capabilities [6]. A product-process model will also describe the relations between the product and the process domain on a generic level, so that for any given component or product, it is possible to determine whether and which equipment would be able to perform the required manufacturing processes. Conversely, the model will provide information on which products or components depend on a given equipment or processes [6]. Several different approaches have been proposed for developing product-process models applying different modelling languages, e.g. cladistics [1], the configurable component [10], or object oriented modelling using the Unified Modelling Language (UML) [6]. Either one of these approaches however provides the possibility to describe the relations between products and the manufacturing system. This will be addressed below in relation to the changeability classes.

It is important to note that product-process modelling can be performed at very different levels of detail. As an example, describing process capabilities at a very high level may be done by characterizing a factory as being able to "produce large steel components". On the other hand process capabilities may be described on a very detailed level, as an example "MIG Weld AISI1005 steel T joint with a 300 Ampere current at 0.1 m/s". Both representations describe steel processes, but at very different levels. Different detail levels would likely imply different benefits in relation to changeability, however in this paper, we address product-process modelling as a general mechanism, not distinguishing between specific levels of detail.

1.3 Example of Product Process Modelling

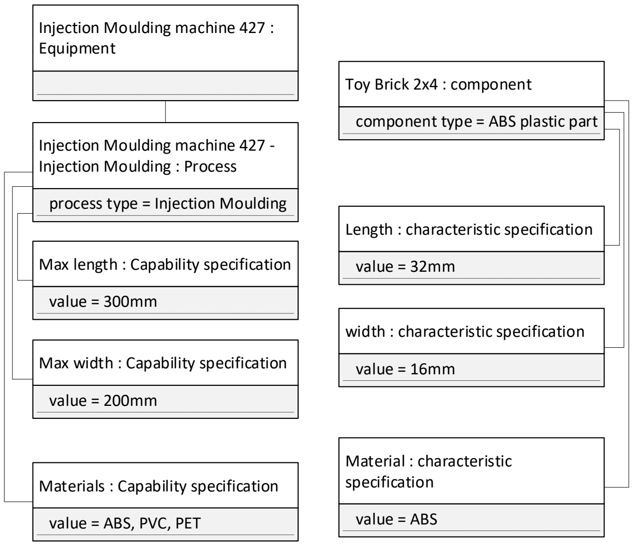
Numerous methods exist for product modelling and process modelling, each serving different purposes. However, to illustrate one approach to do this, the approach introduced recently by the authors of this paper is applied [6]. The basic approach of this method is that in a company applying the method, a company specific ontology is developed, which models the different types of processes exist in a company, and which different types of components the company manufactures. Furthermore, the ontology dictates by which attributes processes and components must be described, and how the component attributes link to the process attributes to be able to determine for any component, which processes would be able to manufacture this. A simple example of such ontology is illustrated in fig. 2. For an injection moulding process.

Fig. 2. Example of a product-process ontology.



Once the ontology is in place, specific equipment implementing the processes can be specified, by assigning values to the attributes. Furthermore, specific components can also be specified, also adhering to the ontology. This is illustrated in fig. 3. By taking this approach, it is ensured that all processes of the same process type are described in exactly the same way, and all components of the same component type are described in the same way. Since the relations between the attributes for the component types and the process types have already been defined generically, this is not necessary to do for the specific instances.

Fig. 3. Example of how specific instances of components and equipment can be modelled based on the ontology in Fig. 2.



2 Analysis of enabling mechanisms

2.1 Changeover ability

The changeability class "Chageover ability" refers to the "operative ability of a single machine or workstation to perform operations on a known workpiece or subassembly at any desired moment with minimal effort and delay" [8].

In relation to achieve changeability on changeovers, product-process modelling can benefit in several different ways. If a model describes the relation between product characteristics and process characteristics, changeover instructions for operators, could be generated automatically based on this information, helping operators achieving faster changeovers. If a model also contains information on the relations between process settings and changeover time, it would also be possible to calculate timing and cost for different sequences of product combinations. This is due to the fact that changeovers from one product to another often depends on how similar these products are. This similarity could be derived from product models, thus indicating the time needed for changing over. This could help in optimizing the production sequence for minimizing changeovers and thus increasing utilization.

2.2 Flexibility

Flexibility is somewhat similar to changeover ability, however flexibility refers to a tactical ability rather than an operative ability and addresses the ability to change a system rather than a machine or workstation [8]. Flexibility concerns the ability to change within products that are already introduced in the production system, i.e. known variety [8]. This happens typically by re-programming, re-scheduling and re-routing the system logically [8].

When having an integrated product-process model which describes product characteristics, process capabilities for specific equipment and the relations between these two domains, it is possible to determine for a specific product, which equipment will be able to perform the required processes. With this information it is possible to generate all feasible routes through a production for a specific product. These alternative feasible routes can form the basis for deciding the actual routing of products through a production. If the process model, or other information repositories hold information on processing cost for different equipment, costs for alternative routings may also be calculated supporting routing decisions even better. Taken even further, the information may utilized for making automated routing of products, without requiring human decisions, given that sufficient priority rules are implemented. This could be one step towards developing a self-optimizing manufacturing system. This will however also require capacity constraints to be implemented in the model.

2.3 Reconfigurability

Reconfigurability is the ability to accommodate larger changes than flexibility. Reconfigurability is thus the tactical ability to alter the manufacturing systems ability to manufacture new product, which are however very similar to those currently being manufactured [8]. Reconfiguration may happen by adding removing or changing the physical structure of the modules in the manufacturing system [8].

Since reconfiguring a manufacturing system changes the capability or capacity, the benefits from the above changeability classes do not apply. This changeability class implies that new products are introduced. When introducing a new product, a product-process model will enable assessment of whether a new product can be manufactured within the current flexibility envelope, or a reconfiguration is in fact necessary. This is possible because the model would specify relations between processes, equipment, and generic product types or component types. Introducing a new specific product, the relations to equipment is immediately known and thus information on which equipment will produce this product is easily available. A part of this information will indicate for which processes the current flexibility is insufficient, requiring new investments in equipment. This relation could also be applied during product development, since different scenarios for changes in products could be evaluated in terms of the required change in the manufacturing system, which could be incorporated into design for manufacturing activities, taking into account equipment investments.

Finally, if a company possesses a manufacturing system platform, containing modules, not currently in use in a specific factory, an integrated product-process model would be able to identify platform equipment which is not currently located in the factory manufacturing the product in question. This could lead to shorter reconfiguration times, since proven solutions for manufacturing equipment can be utilized rather than developing new unproven solutions from scratch.

2.4 Transformability

Transformability refers to the tactical ability to change the structure of an entire factory to accommodate new products or product families, thus implying larger changes than what is addressed with reconfigurability [8]. This is achieved by making larger changes to the factory than reconfiguration, i.e. designing entirely new manufacturing systems with new facilities [8].

The changes which are addressed by transformability is somewhat similar to those addressed by reconfigurability, however differentiated by the magnitude of product change. For this reason, the potential benefits from applying product-process modelling a quite similar. If however a complete rebuild of a manufacturing system is required rather than a reconfiguration, a product-process can be applied to analyze which existing physical equipment can be reused in a future manufacturing system, since the requirements for equipment can be derived from the model and compared to existing equipment. For those processes that cannot be performed by existing equipment, the product-process model can be used to aggregate requirements for process capability as well as requirements for flexibility and possible even reconfigurability. The latter assumes that future minor product changes can be modelled in advance. The same potential benefits related to identifying solutions in a manufacturing system platform also applies to transformability.

3 Discussion and Conclusion

As indicated above, performing integrated product-process modelling where generic processes are linked to generic component types and product types, holds a potential for supporting changeability within different changeability classes. This potential lies in the possibility to support decisions on various levels, from operational to tactical. Also a potential comes from the possibility to automate and make manufacturing systems more autonomous or self-optimizing.

To the authors' knowledge no empirical results have been published on the implementation of such system, and hence it is assumed that no or few companies have actually done this in practice. It is on the other hand observed in several companies, that the task of reconfiguring manufacturing systems, or deciding on a level of flexibility is a difficult task, where companies need tools for supporting the process. An integrated product-process modelling approach would at least contribute to reducing the complexity of these tasks by providing better decision support. It is expected that making such implementation will be a major project, involving several entities within a company. However, the potential benefits are also expected to be significant. Future research will address this by elaborating methods for doing the modelling and running pilot tests on lab manufacturing systems and eventually on real life manufacturing systems.

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