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A Case for Assisting 'Product Family' Manufacturing System Designers

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Abstract

Manufacturing system design is a complex and demanding activity and the system designer has to take many factors into consideration during the development process including the demand and technological requirements of the products or product families. Central to this activity is the synthesis decision making process, during which the designer defines the elements that will make up the manufacturing system. This research identifies in the decision making process a critical activity and contributes a phenomena that can be used by a framework to support designers to address complex issues such as changeability and the evolution of products over the manufacturing system life-cycle.

Keywords: Manufacturing System Design; Synthesis; Product Family

1. Introduction

As defined by Chryssolouris [1] Manufacturing systems are a combination of humans, machinery and equipment that are bound together by a common material and information flow. For this research the authors are also adopting the definition by Chryssolouris of manufacturing system design as the mapping from performance requirements of a manufacturing system onto suitable values of decision variables, which describe the physical design or the manner of operation of the manufacturing system.

Following a review of the challenges in manufacturing system design, this paper sets about analysing the manufacturing system design process with a particular interest in design for product family capability, and the activities which it involves.

The observations and analysis of these challenges are used by the authors to contribute a phenomena describing the effect of manufacturing system design decision consequences on product families. The subsequent argument for the need to assist the manufacturing system designer during the decision making process by making him/her aware of these consequences is then proposed. A review of scientific literature is presented highlighting what tools, methods and strategies are currently provided to manufacturing system designers to support them during this activity.

This research concludes by proposing a framework for supporting manufacturing system designers by providing knowledge of decision consequences on future product variants.

2. Problem statement and motivation

A manufacturing system, which can also be referred to as a production system or facility, forms a part of the factory. The authors will therefore be using the term factory in the following sections to benefit from terms like factory life cycle that have been coined by several authors such as Westkämper [2], Schenk [3], Wiendahl

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[4], who describe the factory life cycle and the several stages of which it consists of.

The authors also recognize manufacturing system design as one of the important stages of the factory life cycle, since it is one of the earliest stages and precedes the process design and ramp-up of the factory.

2.1. Diminishing life-cycles

With diminishing life-cycles also comes a reduction of planning time which leads to an increased pressure on stakeholders to speed up the development process hence take faster decisions. This hypothesis therefore highlights the importance and significance of the conceptual design stages in the factory life-cycle. Hence this leads to highlighting the importance of supporting the stakeholders during these early stages.

This development has led to the introduction and development of Flexible Manufacturing Systems (FMS) in the late 80s to address the need to increase the customizability of a product. Whilst a large amount of research has been carried out in this area, and there were apparent advantages to this technology, the high cost of FMS meant that the take-up from the manufacturing industry was limited.

This has been countered by a strive to develop other approaches such as Transformable Factories [5], Focused Flexibility Manufacturing Systems (FFMS) [6], Reconfigurable Manufacturing Systems (RMS) [7] which can be grouped under the generic term of Changeable Manufacturing. Wiendahl [8] defines changeability as “Changeability in this context is defined as characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically”.
As can be imagined several stakeholders are involved and responsible for developing the manufacturing system on many levels (layout, production system, cell, machine). Based on the concept of the digital factory design cycle developed by Westkämper [2] these stakeholders carry out the factory design activity starting with a product design in mind.

2.2. Costs committed during the factory life cycle

Fig. 1 presents a model which compares the actual expenditure with the committed costs during the different phases of the factory life-cycle based on an analogy of the model developed by Cooper & Kaplan [9] which compares the actual expenditure with the committed costs during the different phases of product design. By analysing this model one can note that during the early stages the incurred costs are low giving a low cost incidence. On the other hand many decisions are taken during these early stages, meaning that the committed costs are significantly larger.

Therefore the hypothesis that is being proposed here is that during the early stages of the Factory Life-Cycle few costs are actually spent, but since many decisions are being made during these stages this means that substantial costs are being committed.

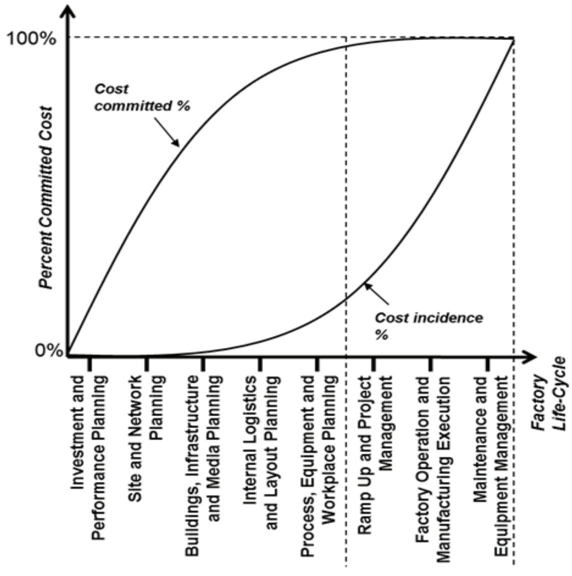

Fig. 1. Costs committed vs. cost incidence during the Factory Life-Cycle

2.3. Concurrent consideration in manufacturing system design

As described by Constantinescu in [10] the factory and product are developed concurrently to each other with decisions being made during the planning phases of the independent life-cycles affecting each other. The two life-cycles then meet at what is defined as the crossing life cycles point where the product is produced by the manufacturing system. Several other authors highlight this concurrent or integrated [11] development with one of the main aims to include concurrent consideration during development. This concurrent consideration leads to the foreseeing of possible problems that product design decisions have on other phases such as manufacturing system design or production and vice-versa.

2.4. Motivation

As outlined by Westkämper [12] and Wiendahl et al. [8] manufacturers are facing several challenges in the current industrial scenario. Some of the biggest challenges include an increase in the customization requirement of products and a decrease in the product life-cycle. Manufacturing system designers are being expected to consider more issues concerning the total factory life cycle when generating design solutions.

Design decisions generate consequences, these can be intended or unintended, good or bad. Knowledge of such consequences is distributed amongst various stakeholders both in the manufacturing and design teams.

Having reviewed these challenges the motivation for this research lies in providing a framework for supporting and assisting manufacturing system designers to foresee the consequence of their decisions on the factory life cycle and product families.

3. Migration of synthesis decision making for product design to manufacturing system design

Roozenburg [13] defines Synthesis as the combining, assembling, mixing or compounding of anything in to a new whole. If we consider the term synthesis in manufacturing system design then this refers to the action of choosing, mixing or compounding from a number of options, such as machines and material handling equipment, into a new manufacturing system.

Borg et al [14] have provided such an approach in the model which is shown in Fig. 2. The designer carries out a commitment action during synthesis by which s/he chooses one of the possible options based on the requirements that have to be fulfilled, the circumstances in which the decision is made and the preferences of the designer. This synthesis commitment is then added to the evolving artefact model, in a part-of relationship.

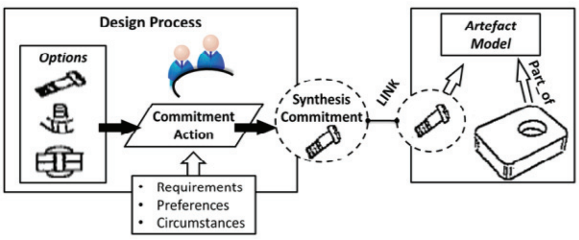

Fig. 2. Link Caused by Synthesis Decision Commitments [14]

When analysing in detail the decision making activity in manufacturing system design, one can find many analogies to that of product design. In line with the factory as a product paradigm by Westkämper [15] one can consider products and manufacturing facilities as technical systems and the above model can be applied to synthesis decision making in manufacturing system design.

Hence when considering this model from a manufacturing system design approach, the product or the elements that make up the product can be viewed as the requirement or specification of the manufacturing design problem.

During synthesis the manufacturing system designer then chooses a number of elements or machines that create an evolving and tentative solution.

Therefore the model developed by Borg can be applied to synthesis decision making in manufacturing system design. This research is therefore proposing the migration of the product synthesis design making model to a manufacturing synthesis decision making model (Fig. 3).

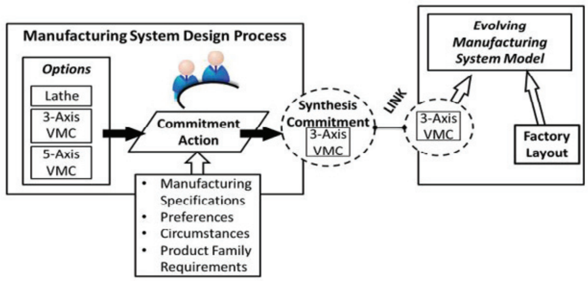

Fig. 3. Manufacturing System Design Synthesis

As shown by this model the product development process for product families would add further requirements that have to be achieved by the manufacturing system. Hence it increases the complexity of the synthesis decision making process, and further justifies the need to support such an activity.

4. A manufacturing system design phenomena

The phenomena described in this section was observed when analysing the synthesis decision making activity in manufacturing system design. Understanding this phenomena lead the researchers to develop a framework to support manufacturing system designers.

4.1. Consequences in manufacturing system design on the factory and product life-cycles

In [16] ElMaraghy proposes a new design framework that maps the effects of changes in product design on the manufacturing system and vice-versa in terms of capability. Based on this framework and on the Theory of Dispositions by Olesen [17] this paper implies that each decision made by the manufacturing system designer has a consequence on both the factory life-cycle and the product life-cycle.

As per the crossing life-cycle model, the factory life-cycle and the product life-cycle are inexorably linked. Therefore it can be concluded that decision consequences in manufacturing system design have repercussions also on the product life-cycle.

4.2. Intentional and unintentional consequences

There are two types of consequences that can be identified; these are intended or unintended consequences. Based on the work carried out by Borg et al in [14] the following four scenarios can result from synthesis decision commitments in manufacturing system design. The first scenario results when a designer makes a decision commitment to achieve an intended good consequence. This can be described as the goal of the designer, for example choosing an injection moulding machine to produce plastic parts.

The second scenario results when the intended decision commitment leads to an intended and problematic consequence. Although possible this scenario is not probable as responsible manufacturing engineers would avoid this situation. The third scenario describes a case where the decisions made lead to intended good and unintended problematic consequence. So for example this could happen when a designer chooses an injection moulding machine to produce plastic parts, but the choice of this machine can lead to a problematic consequence, such as the heavy vibrations caused by the machine affecting other processes making it problematic for production personnel.

Finally the last scenario describes a cases were the decision made generates both intended and unintended good consequences. An example of this would be that if the designer choses an injection moulding machine to process black plastic parts, this same machine can also be used to produce other coloured plastic parts. Hence if the product designer adds a new product family member with a distinguishing colour, then no further investment is needed since the same machine can be used.

4.3. Consequences in manufacturing system design on product families

Therefore as seen in sections 4.1 and 4.2 the following phenomena can be described; Decision commitments made during manufacturing system design synthesis can have intended or unintended consequences that can be both good and/or problematic on both the factory life-cycle and the product life-cycle.

This phenomena has a greater relevance when the design of the manufacturing system has to cater for product families, especially when considering the theory of evolving product proposed by ElMaraghy [18] and the co-evolution model proposed by Tolio et al. in [19].

This therefore proves the case for supporting manufacturing system designers especially when dealing with the possibility of product families. The following sections will therefore review what are the current tools offering support, and then present a new framework for assisting manufacturing system designers.

5. Support of early manufacturing system design for product families

There are several systems, tools or approaches aimed at supporting the decision making activities in manufacturing system design. This section presents a review of such tools and attempts to provide an overview of the current state of the art.

Manufacturing system design support is provided mainly in terms of approaches or methods but these could also include simulation systems such as that proposed by Qiao et al. [20] for modelling of mass customization manufacturing (MCM) systems with the use of Petri Nets. AlGeddawy [21] proposes a new mathematical model to discover the embedded knowledge governing the relationships between product features and the needed manufacturing capabilities. This knowledge is then used to synthesize new manufacturing capabilities and systems for the new products. Piedade et al. [22] describe an approach based on a Virtual Factory Framework in factory planning with the aim of improving the ability to generate better and more sustainable solutions over the entire factory life-cycle

In manufacturing system design for co-evolving products and manufacturing systems, uncertainty plays a central role. Janz et al. [23] provide an approach that allows for a sustainable evaluation of manufacturing alternatives in the early stages of product development combining different methods of processing uncertain information related to product manufacturing alternatives.

In supporting manufacturing system design for product families it is inevitable not to consider tools that support decision making in Flexible and Reconfigurable Manufacturing Systems. Since the introduction of flexible manufacturing systems, a number of decision support systems have been proposed for flexible manufacturing system design.

The method proposed by Abele et al. [24] proposes to support investment decisions in flexible manufacturing system design by presenting a methodical concept for the evaluation of manufacturing systems using real options in order to incorporate flexibility. Grieco and Nucci [25] used a modelling and simulation tool to automatically simulate a set of different scenarios and to provide the necessary capability to compare the performance of focused flexibility manufacturing systems to flexible manufacturing systems.

On the other hand there are also a range of tools for decision support for product family decisions. For example Zha et al. [26] present a knowledge-modeling framework and prototype system that can be used for platform product design knowledge capture, representation and management with the aim of supporting the product family design process.

In summary the above approaches mainly provide support of the manufacturing system decision making activity late in the design stage after synthesis has occurred at the analysis stage. Whilst these tools further prove the need for supporting manufacturing system design, and they cover a wide range of support, they do not assist designers proactively and during the synthesis decision making activity itself by providing guidance of design consequences, hence the need for developing the framework presented in the following section.

6. A framework for supporting manufacturing system designers

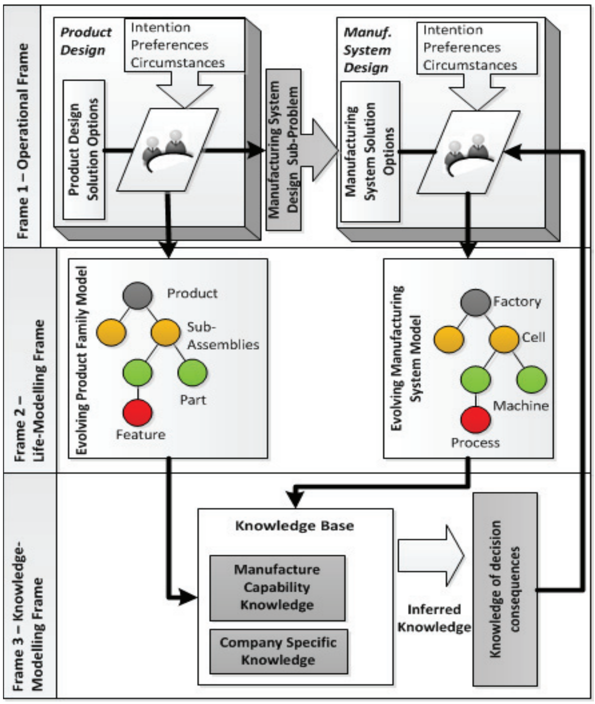

Fig. 4. Framework for supporting manufacturing system designers

The underlying framework philosophy being presented here allows the manufacturing system designer to explore a number of different manufacturing system solutions and is presented with consequence of each decision. Therefore this approach framework aims to reveal and analyse the consequences of commitments made during the manufacturing system design on product families (Fig. 4).

The framework is therefore being developed to support the manufacturing system design processes by proactively providing the necessary consequence information and required guidance.

More importantly, it focuses on "product family and manufacturing system" synthesis decision making. In this way support is provided when the system solution model is still evolving and therefore helping to proactively foresee and optimize as early as possible the range of product families that can be handled during the product and factory life-cycles.

6.1. Operational Frame

As the product design solution evolves, the product designer and factory planner start to concurrently solve sub-problems encountered in both product and manufacturing system design.

The commitments made are based on a set of intentions, preferences and circumstances. This means that the factory planner might commit to different decisions based on the company's current economic circumstances. The input to this frame is therefore a customer requirement or specification. The product designer and manufacturing system designer will then interact with a synthesis element library. The stakeholders can then search the options for a solution to the sub-problems encountered. The outputs of this frame are the elements that have been chosen by the designers.

6.2. Life-Modelling Frame

The elements which the product designer and manufacturing system have committed to are the input of the next frame. These elements are added to the evolving system models. Therefore if the product designer commits to having a plastic part, then this will be reflected in the evolving product model.

This will drive the factory planner into solving the manufacturing system sub problem of manufacturing this plastic part. From a set of options, such as machining, plastic injection moulding or extrusion, the factory designer can then commit to a process to manufacture this part. This commitment will then be added to the evolving manufacturing system model. The outputs for this frame are the evolving product and manufacturing system models.

6.3. Knowledge Modelling Frame

From the previously explained relationships between products, manufacturing systems and changeability one can elicit the type of knowledge and knowledge structuring which is required to foresee the consequences on product variability from decisions made, and therefore provide feedback to the user.

The inputs of the evolving product and manufacturing system models are constantly being monitored to infer new knowledge of current consequences of decisions being made. The output is therefore the support, in terms of knowledge about decision consequences, which is fed back to the designer. In this method the stakeholder can proactively monitor the effect of the elements chosen on the product families which can be produced by the manufacturing system in development.

7. Conclusions and future work

The arguments presented in this paper highlight the need for manufacturing system designers to be supported during the synthesis decision making activity.

This paper hence contributed a phenomena that explains the consequences of decisions made during manufacturing synthesis design on the factory life cycle and the product families that can be handled by the evolving and future manufacturing system. Together with a review of the state of the art and the proper understanding of the design problem being addressed, this phenomena was the fundamental concept behind developing a design support framework. The aim of this framework is to support the manufacturing system designer by proactively foreseeing and optimizing as early as possible the range of product families that can be handled by the evolving manufacturing system.

This research and its implications will now lead to the development of a tool based on the framework proposed and to an industrial evaluation, with the use of a number of case studies and concrete industrial data, to prove the validity of the arguments proposed.

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