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Development and evaluation of a knowledge-based decision-making approach for designing changeable manufacturing systems

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ABSTRACT

Due to highly competitive markets, constantly shifting consumer requirements, and technological advances, product families are continuously evolving over time. This product evolution leads to new part variants being added to the existing part mix. When at a future time the manufacturing system is not capable, as is or in a reconFigured state, to manufacture the evolved part variants, then this has negative consequences on business performance. This phenomena is being termed as disruptive product evolution.

Due to complex interdependencies, incomplete information and uncertainty in manufacturing requirements this phenomena leads to a wicked problem. In order to tame such a wicked problem, this paper contributes and evaluates a knowledge-based decision-making approach that supports manufacturing system designers in exploring the interplay between business strategy, evolving product range and manufacturing systems. A prototype digital factory tool based on this approach has been developed and evaluated. The encouraging results obtained have shown that this research paves the way for the development and integration of such knowledge-based decision-making approaches within state of the art digital factory tools.

Introduction

Implications of product and manufacturing system co-evolution

Changes in Manufacturing Systems (MSs) can trace their origin in customer behavior and changing product requirements. Due to highly competitive markets, constantly shifting consumer requirements, and technological advances, product ranges are constantly evolving over time. The product range continuously evolve with the addition of new features or parts that may be added or replaced to the current range of products [1]. The dynamic nature of customer requirements has been described as a constantly moving target [2], thus presenting a significant challenge for several aspects of product development.

As outlined by ElMaraghy [3], a change in the product range can be translated through a process matrix to the manufacturing domain, which causes changes in the MS design and production processes. Hence as explained by Francalanza et al. [4] decisions made during the design stage of the MS have outstanding consequences on both the life cycle of the MS and also on the future product range which can be produced by the MS. This makes the early stages of factory planning, when MS design commitments are being made, critical to the future capability of the MS. It is therefore critical to provide support early in the life-cycle of the MS, when the costs committed are low when compared to actual costs [5].

Factories and MSs that have been planned to manufacture a range of products have longer life cycles than the products which they produce [6]. Hence the inherent nature of factories means that they need to be capable of producing different product ranges throughout their life cycle. This paradigm brings about an additional complexity to MS design since products continue to evolve throughout the life-cycle of a MS, leading to a phenomena termed co-evolution [7].

This research argues that when designing a new MS, the MS designer has to consider and analyze not only the current product range requirements but ideally also how the product range may evolve over time. All of this within the parameters of the company's business strategy.

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Manufacturing system changeability

As explained in this introduction an important requirement for modern factories is the need to deal with product ranges and their evolution over time [7]. One of the approaches utilized by MS designers, in order to deal with these challenges, is the introduction of manufacturing changeability. The practice of designing MSs with a degree of changeability has been developed in order for MS designers to deal with the challenges brought about by product evolution. Wiendahl [8] defines changeability as "... the characteristic to accomplish early and foresighted adjustments of the factory's structures and processes on all levels to change impulses economically". Systematic CMS design approaches are required in order to develop and deploy CMSs in industry.

When evolving product ranges are a requirement of the MS, then MS designers have to apply changeable manufacturing concepts such as transformable factories [9], focused flexibility manufacturing systems (FFMS) [10], reconfigurable manufacturing systems (RMS) [11].

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. MS designers are expected to consider more issues concerning the total factory life cycle when generating design solutions.

Westkämper [13] in his analysis of the Manu*Future* document discusses several pressures to change the paradigms of industrial manufacture for the European industry to remain competitive under increased economic uncertainty, in the future. In the implementation of Manu*Future*, one of the driving forces identified is the application of ICT in manufacturing.

Designing changeable manufacturing systems (CMSs) brings about other significant challenges. As explained in [14] the variety introduced in product ranges brings with it increased complexity in process planning and MS design. When considering the evolution of product ranges over time then one easily conceives what complex interactions take place as the solution evolves. These challenges increase when taken in the context of the MS designer's capability to perform complex reasoning.

CMS decision making knowledge and human cognition capability

The common attribute to all forms of human originated design is the human brain, since as described by Finger et al. [15] much of the design process is a mental process. As with all activities related to the human brain we can therefore infer that the design activity can be described as a complex activity. A study carried out by Kim et al. [16] shows that there are three cognitive operations between working memory and long term memory: memory retrieval, association and transformation in order to generate early design solutions. An important aspect to consider is that human stakeholders are limited by their mental brain capacity, in what is defined as the human brain's working memory [17]. This limitation hinders the ability to detect the many causal and interacting patterns between CMS commitments made to the factory solution and the evolving product, process and business solutions.

Motivation

As argued in [18] an integrated approach is required to proactively provide the required CMS design knowledge that minimizes or avoids the disruptions caused by product evolution. This knowledge needs to be provided at the right time whilst not being intrusive to the designer's cognitive activity [18].

To deal with the complexity of the MS design activity with a manual method would lead to a time consuming, and complex support tool which is hard to implement, and difficult to use. Therefore the application of an ICT based tool to implement this method would lend itself well to this problem. Design decisions generate consequences, [5] 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 an approach framework for supporting and assisting MS designers to foresee the consequence of their decisions on the factory life cycle and product families.

Developing a digital factory tool for supporting CMS design

As defined in VDI 4499 [19], the aim of the digital factory is the holistic planning, evaluation and ongoing improvement of all the main structures, processes and resources of the real factory in conjunction with the product. Fig. 1 portrays a framework for the development a digital factory tool that provides intelligent support. This computational tool development framework has been adapted from the works of Duffy and Andreasen [20] who utilize a similar framework for the development of computational models and tools for product design.

The support which is required is primarily derived from the reality which is studied and the area of influence identified. Phenomena models are descriptive models based on this reality. The knowledge model is a formal representation of the phenomena model, and defines the type of knowledge and knowledge structures. A design approach framework that describes how the structured knowledge models can be utilized to provide intelligent support to the CMS designer also forms part of the knowledge

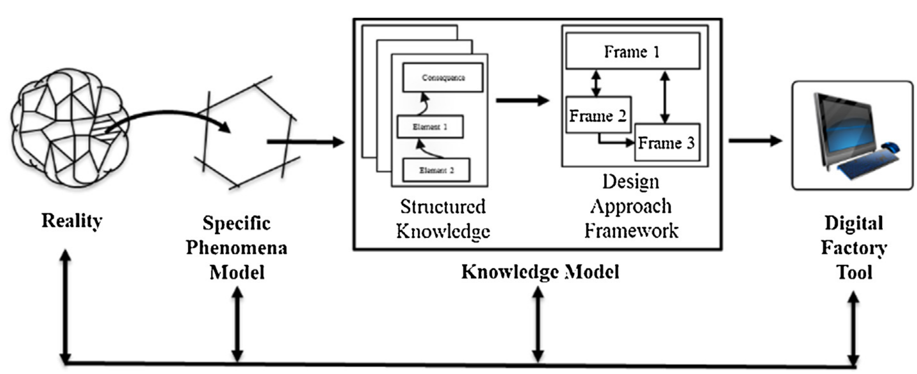

Fig. 1. Intelligent digital factory tool development framework – adapted from [9].

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