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A knowledge-based tool for designing cyber physical production systems

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ABSTRACT

Changing production systems and product requirements can trace their origin in volatile customer behaviour and evolving product requirements. This dynamic nature of customer requirements has been described as a constantly moving target, thus presenting a significant challenge for several aspects of product development. To deal with this constant and sometimes unpredictable product evolution, cyber physical production systems (CPPS) that employ condition monitoring, self-awareness and reconfigurability principles, have to be designed and implemented. This research contributes a CPPS design approach that proactively provides the required CPPS design knowledge. This approach aims to minimise or avoids future consequences and disruptions on the CPPS. This knowledge needs to be provided at the right time whilst not being intrusive to the production system designer's cognitive activity. To effectively deal with the complexity of the cyber physical production system 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. The CPPS design approach has therefore been implemented in a prototype digital factory tool. This paper describes in detail the system requirements and system architecture for this tool. In order to establish the effectiveness of the proposed approach for designing cyber physical production systems, the prototype digital factory tool has been evaluated with a case study and a number of semi-structured interviews with both industrial and scientific stakeholders. The encouraging results obtained from this research evaluation have shown that such an approach for supporting the CPPS design activity makes stakeholders aware of their decision consequences and is useful in practice. This result can lead the way for the development and integration of such knowledge-based decision-making approaches within state-of-the-art digital factory and Computer Aided Engineering Design (CAED) tools.

1. Introduction

Advances in technologies such as low power electronics and wireless communications are bringing about a new reality of connectivity in our daily lives. The "Internet of Things (IoT)" and "Cyber Physical Systems (CPS)" [1] are terms that have been coined to describe these engineered and connected systems, which have embedded computational and networking capabilities.

From a manufacturing perspective the development of technologies such as smart sensors [2], RFID [3], grid [4] and cloud [5] manufacturing, are pushing towards a fourth industrial evolution, or as defined by the German Federal Minister of Education and Research, Industry 4.0 [6]. The implementation of Industry 4.0 in manufacturing environments comes about with the development and full industrial implementation of Cyber Physical Production Systems, (CPPS). CPPS consist of autonomous and cooperative elements (e.g. Smart Machines) and sub-systems (e.g. Smart Factories) that are connected with each other in situation dependent ways, on and across all levels of production, from the processes level up to factory and production levels [7].

As noted by Monostori [7], historically there is a parallel development between manufacturing, ICT and computer systems. Development of microprocessors, networks and databases in the 80's led to the development of computer-integrated manufacturing (CIM). Following these developments, the application of artificial intelligence (AI) and machine learning led to the development of Intelligent Manufacturing Systems (IMS) [8]. The increased demands of dynamic economies, together with the need to analyse an ever increasing amount of data gathered from all levels of factory operation, has driven the development of smart

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manufacturing and smart factories [9], which can otherwise be defined as CPPS.

The digital factory [10] has been proposed in order to support the implementation of factories through the use of virtual environments and representations that supplement the real productions systems across the factory life cycle [11]. As defined in VDI 4499 [12], 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. As explained by Choi in [13], there are still barriers between the implementation of the digital and smart factory, hence CPPS, which require further work, especially to account for the complexity of CPPS and the high degree of variability in CPPS requirements.

To address these barriers, methods and approaches for designing CPPS are required. This research therefore contributes a CPPS design approach that proactively provides the required CPPS design knowledge to the production system designer. In order to adequately report the research results, Section 2 of this paper brings to light the specific problem which has been addressed by this research work. Following which the state-of-the-art in tools which support the CPPS design activity is presented in Section 3. A knowledge-based CPPS design approach, phenomena and knowledge models on which the digital factory tool is based are then presented in Sections 4–6 respectively. The main contribution of this paper, a prototype digital factory tool and system architecture which represent the implementation of the knowledge-based CPPS design approach are described in Section 7. Section 8 presents the evaluation methodology and results adopted by this research. Future work and the conclusions of this research work are presented in Section 9.

2. Problem definition

One of the main drivers for the implementation of CPPS is the need for continuous adaptability and evolution of the production system [7]. Evolving production system requirements can trace their origin in volatile customer behaviour and evolving products [14]. This dynamic nature of customer requirements has been described as a constantly moving target, thus presenting a significant challenge for several aspects of product development [15]. In order to verify whether the evolution of production system requirements is a problem encountered in industrial reality, this research conducted a questionnaire with eight practicing production system designers. Participants to this questionnaire all came from an industrial environment, with an experience of between 5 and 30 years, in various industrial fields such as automotive, medical and consumer products. The participants were asked if they have encountered problems when introducing the production of new product variants to existing production systems. The response to this question was that all the participants have encountered problems when new product variants need to be introduced to existing production systems.

2.1. Uncertainty in product evolution

As previously explained in the introduction to deal with the uncertainty and unpredictability of product evolution, CPPS have to employ the characteristics of changeability, networkability, and distributed control structures. It is argued by this research that due to this inherent complexity, during the design of CPPS production system designers make decision commitments which result in unintentional and problematic consequences on several stages of the factory life cycle. These include CPPS aspects such as capability, adaptability, networkability and security. As explained by Lee [16], in order to solve the challenges posed in the development of CPS, approaches and tools are required to support the design activity. Since CPPS share the same principles, enablers and expectations of CPS [7], it is hereby argued that the need to develop approaches and tools to support the design activity can also be extended to CPPS. This gap has also been identified by Fisher et al. [17] who recognise the need for methodologies, tools and models that ease part of the CPPS design problem.

2.2. Research problem

As explained by Bannat et al. [18] a key component for adaptive and reactive production systems are still human planners with their highly developed cognitive capabilities such as perceiving, planning, learning and acting. The common attribute to all forms of human originated design is the human brain, since much of the design process is a mental process. As with all activities related to the human brain we can therefore surmise that the CPPS design activity can be described as a complex activity. 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 [19].

Therefore an approach is required to proactively provide knowledge-based support during the CPPS design process in order to minimise or avoid unintentional and problematic consequences. This knowledge needs to be provided at the right time and with the right context, whilst not being intrusive to the production system designer's cognitive activity. To effectively deal with the complexity of the CPPS 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 a computational, digital factory tool to implement this method lends itself well to this problem. The scientific research problem is therefore concerned with developing a computational approach that provides production system designers with solution related knowledge, when generating and describing CPPSs.

2.3. Solution requirements

From Monostori's definition of CPPS [7] and the works of [20] and [17] we can surmise that CPPS need to be designed to employ the characteristics of adaptability, distributed and cognitive control. CPPS have to be adaptable and evolvable to meet their changing requirements. This evolution can occur in both the product and process requirements. Moreover, CPPS need to implement the paradigms and enablers of flexible, reconfigurable and transformable manufacturing. This vision of glocalized CPPS [21] is achieved by using machines that have embedded processing and networking capabilities. These capabilities allow the possibility for the third characteristic of distributed and cognitive control. The capability to use cognitive processing to analyse data, through data mining and machine learning, gathered from machine sensors allows for the decentralisation of the CPPS control.

Hence a solution is required which makes production system designers aware of the potential negative consequence of CPPS design decisions on the capability and performance of the CPPS during the CPPS synthesis design activity. These negative consequences are termed by this research as Factory Life Cycle Consequences (FLCCs). This research hence argues that to provide such a solution, knowledge of the CPPS, the evolving CPPS requirements and CPPS design rules which reveal FLCCs are required.

3. State of the art in CPPS design

This section presents a review of the state of the art research in approaches which support CPPS design. Whilst CPPS are still in the