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An application of physical flexibility and software reconfigurability for the automation of battery module assembly

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Abstract

Batteries are a strategic technology to decarbonize conventional automotive powertrains and enable energy policy turnaround from fossil fuels to renewable energy. The demand for battery packs is rising, but they remain unable to compete with conventional technologies, primarily due to higher costs. Major sources of cost remain in manufacturing and assembly. These costs can be attributed to a need for high product quality, material handling complexity, uncertain and fluctuating production volumes, and an unpredictable breadth of product variants. This research paper applies the paradigms of flexibility from a mechanical engineering perspective, and reconfigurability from a software perspective to form a holistic, integrated manufacturing solution to better realize product variants. This allows manufacturers to de-risk investment as there is increased confidence that a facility can meet new requirements with reduced effort, and also shows how part of the vision of Industry 4.0 associated with the integration and exploitation of data can be fulfilled. A functional decomposition of battery packs is used to develop a foundational understanding of how changes in customer requirements can result in physical product changes. A Product, Process, and Resource (PPR) methodology is employed to link physical product characteristics to physical and logical characteristics of resources. This mapping is leveraged to enable the design of a gripper with focused flexibility by the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich, as it is acknowledged that mechanical changes are challenging to realize within industrial manufacturing facilities. Reconfigurability is realised through exploitation of data integration across the PPR domains, through the extension of the capabilities of a non-commercial virtual engineering toolset developed by the Automation Systems Group at the University of Warwick. The work shows an "end-to-end" approach that practically demonstrates the application of the flexibility and reconfigurability paradigms within an industrial engineering context.

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Keywords: battery module assembly; reconfigurability; flexibility; virtual engineering

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1. Introduction

Efforts are being made to transition society towards renewable energy technologies, driven by policy and legislation, due to the threat posed by increases in greenhouse gas emissions and combustion pollutants [1]. It is estimated that currently 25% of CO_2 emissions can be attributed to the transport sector; this is projected to rise to 50% by 2030 if current trends continue [2]. Electric vehicles are a potential solution as sufficient deployment will reduce pollutants, greenhouse gases, and offer significant well-to-wheel efficiency improvements [3]. There are a range of automotive propulsion system configurations ranging from mild-hybrids to purely electric systems. Irrespective of architecture however, batteries remain a common key enabler of electrification for energy storage within and external to the automotive sector [4]. A breadth of applications for battery technologies is anticipated within the coming years which bring with them a broad range of potential variants and product types that may need to be produced by a single production system. The degree of variety is difficult to predict and so engineers are compelled to design manufacturing systems to be able to accommodate change. This need aligns with the vision of Industry 4.0, where connectivity across all levels of the business and through the

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product and system lifecycles facilitates manufacturing agility and proactivity [5].

Two major phases of a system lifecycle are design and re-engineering/reconfiguration. At the initial design phase, a number of considerations need to be made, one of which is to try and anticipate the breadth of capability the system needs with respect to product requirements. Reconfiguration phases are often driven by changes to the product or new product introduction. In order to reduce the time and accompanying costs associated with this phase, it is beneficial to know i) the nature of the system changes, and ii) a mechanism for executing the change with minimal human intervention. Some common existing paradigms associated with change within manufacturing systems are flexibility and reconfigurability. However, formal implementation of these concepts within the engineering workflow during the system design and reconfiguration phases is limited. In line with the vision of Industry 4.0, this study proposes that the integration of product realisation domains (Product, Process and Resource (PPR)) through lifecycles within engineering tools is fundamental in managing change. The approach is demonstrated on the introduction of a new variant in a battery module assembly system.

2. Literature Review

2.1. *Digital Manufacturing*

Digital Manufacturing is one of the disciplines within Product Lifecycle Management (PLM) [6], where Computer Aided Design (CAD) and Computer Aided Engineering data plays a vital role in managing products and systems through their respective lifecycles. The concept of Digital Planning Validation is discussed in [7], where the validation of a product's produce-ability is done parallel to the production planning phase in a digital environment. Having validated the plans virtually, training materials for operators can be generated and used. Digital Mock-Ups discussed in [8] are used to simulate a production system to verify and validate system configurations, layouts, and process plans. Integration of digital models with the physical system is done during the commissioning phase, often to validate programmable logic controller (PLC) software. This has been demonstrated in [9] through the use of Logic Control Modeling connected to DELMIA Automation V5, and Tecnomatix eM-PLC from Siemens. Beyond this point, however, digital models see limited use as they are not maintained post the build and commissioning phases. Thus, during reconfiguration there is limited support from digital manufacturing or PLM tools. For example, translation of changes in product features through to machine control parameters within PLC programs remains an entirely manual process, supported through ad-hoc methods [10,11]. As a result, despite the benefits of the digital manufacturing paradigm at the design phase, its value with respect to supporting and executing flexibility and reconfigurability on the shop floor is limited.

2.2. Flexibility and Reconfigurability

There are many definitions for flexibility, reconfigurability, and related terms within the literature. Following ElMaraghy, for example, the ability of production systems to be adaptable to continuous changes is described as changeability [12]. Forming a subcategory of changeability, flexibility is related to the assembly system, while reconfigurability refers to the entire production area including logistics [12]. The authors have chosen the definiton put forward by Koren ([13,14]): "flexibility is the general ability to respond to changes in production volume or product variants in a fast and global cost efficient way without changing elements of the production line" [13], as it aligns with the approach presented in this paper. A design framework for flexible systems is proposed in [24]. It consists of four stages supported by process management. The baseline design assists designers in the early design process using known configurations. This is followed by the uncertainty recognition which is to help identify the range of flexibility. In the concept generation phase, concepts are generated to handle the identified range of flexibility. Finally, designers analyse and evaluate the generated concepts. The proposed taxonomy and further literature [25] focus on the system level. A detailed methodology for the design of flexible system components for a production system is absent in the literature.

Design methodologies for flexible production system are needed to achieve reconfigurability. Reconfigurability is considered a subset of flexibility [15]. It is the ability to change the capability of production equipment by adding or removing functional elements in a short time and with low effort to meet new requirements within a part family [13]. Reconfigurability within the software domain is addressed by [16] who discusses issues faced with automatic software reconfiguration such as: the absence of a formal procedure for implementation, limited application of the available methods, and the need to reconfigure all processes simultaneously. According to [17], within the context of manufacturing, software reconfiguration for control systems is considered a key enabler for reconfigurable manufacturing systems (RMS). Self-adapting control software is created through integration with a mechatronic model, reducing post reconfiguration system ramp up time [17]. A reconfigurable control architecture that can adapt to changes has been proposed by [18], in which component based development has been combined with holonic manufacturing system to provide an architecture for a decentralized manufacturing system. In [19], a framework is proposed to translate the assembly sequence change necessitated as a consequence of product variant introduction to the control system logic through virtual engineering tools. In [20], a PPR ontology knowledge-driven approach, enables increased reactivity to change. Despite the advancements in software reconfiguration, according to [21], the inability of the current PLCs to help realise RMS, is an inhibitor to the implementation of control software reconfiguration. One reason for this is the current use of the IEC 61131-3 standard as it does not favour dynamic reconfiguration. However, the IEC 61499 standard is sought to address this issue as it more suitable for reconfiguration [22], however gaining industrial acceptance for this standard has proved to be a challenge [23]. Despite these advances, reconfiguration at the field device level still needs to be supported by the wider engineering lifecycle, which at present lacks suitable engineering tools and methods [17].