Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 63 (2017) 604 – 609

www.elsevier.com/locate/procedia

The 50th CIRP Conference on Manufacturing Systems

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

Malarvizhi Kaniappan Chinnathai[a]*, Till Günther[b], Mussawar Ahmad[a], Cosima Stocker[b], Lukas Richter[b], David Schreiner[b], Daniel Vera[a], Gunther Reinhart[b], Robert Harrison[a]

[a]*Automation Systems Group, WMG, University of Warwick, CV4 7AL, West Midlands, UK*
[b]*Institute for Machine Tools and Industrial Management (iwb), Technical University of Munich (TUM), Boltzmannstr. 15, D-85748 Garching, Germany*

* Corresponding author. *E-mail address: M.Kaniappan-Chinnathai.1@warwick.ac.uk*

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.

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

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

doi:10.1016/j.procir.2017.03.128

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].

2.3. Summary

The importance of flexibility and reconfigurability is recognized, but due to limited formal, structured engineering processes and links across domains, true realisation of these paradigms remain hamstrung by inefficient workflows. Therefore, this paper proposes a PPR framework that demonstrates i) how manufacturing system components should be designed to have sufficient flexibility for the anticipated product variety i.e. focused flexibility, and ii) an engineering workflow that supports reconfiguration through the use of component-based virtual engineering tools.

3. Approach

3.1. PPR framework

A **PPR framework** is used in this work as described in Fig. 1. At the highest level, the product drives the process, which in turn drives the resource. At the point of resource existence in the physical (or digital) world, it begins to constrain the process which in turn constrains product design. This set of assumptions is used to drive the **component design process** with sufficient flexibility to accommodate a range of product variants and consequently, a range of process parameters through a requirements list (Section 3.2). The design information is instantiated into a set of **virtual engineering** tools which support the system through its lifecycle. As such, common data models can be used both in the design phase and later in the operation phase to support reconfiguration, exploiting the flexibility designed into the system (Section 3.3).

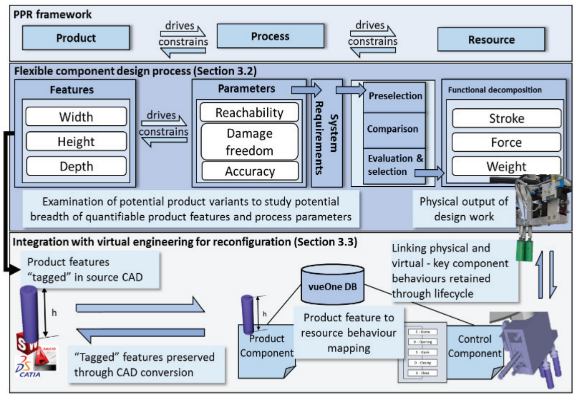

Fig. 1. PPR framework with flexible manufacturing system component design, and reconfigurability through virtual engineering.

3.2. Product/Process parameter selection for machine component design

A requirements list based on product/process parameters is created and developed iteratively. Firstly, general requirements e.g. safety, environment, interfaces etc., are identified; this is a system level view. Next, a deep-dive on product requirements is carried out, analysing all members of a focused product family. At this point, key product **features** are extracted from the overall parameter set e.g. width, height, depth (Fig. 1), to extract basic product designs in the form of topologies. These topologies build the basis for a heuristic solution search.

Next, the process **parameters** are investigated which include: reachability, freedom of damage, and positional accuracy (Fig. 1). After a general **preselection**, the derivation of the requirements is classified into demand and request by the comparison of couples (**comparison**, Fig. 1). A Pareto analysis is conducted to split mandatory from optional requirements to reduce complexity. Once all appropriate requirements have been captured, Resource domain parameters are defined. The physical description of necessary skills is derived from range definitions. The necessary skills identified define the functional structure of the Resource component. Through **functional decomposition** into subfunctions, operating principle selection is enabled using a morphological analysis. Based on the set of operating principles, potential concepts are generated. Any concept to be further detailed is selected through a utility analysis which uses the evaluation criteria from the initial requirements list. During the selection process, those solutions that offer the ability to rapidly reconfigure through software i.e. mechatronics, are most favourable, despite not having lowest initial investment cost. System reconfiguration offered through software modifications provides compatibility with the Industry 4.0 vision. The following section describes how engineering tools can use design data to support reconfiguration to exploit the flexibility designed into the system.

3.3. vueOne toolset for supporting reconfiguration

vueOne is an engineering toolset that supports the lifecycle of a production system. It was developed by the Automation Systems Group at the University of Warwick. Within the tools, extensible component-based data models support process planning, system configuration, code generation and deployment, commissioning, maintenance, operational analytics, and system reconfiguration [26]. Geometries for system components are converted from native CAD formats to VRML/X3D and form a part of a software component within the tool, uniquely identified through an ID. This assists the identification and management of the components in later stages of the product lifecycle. During the process planning phase, system behaviour is modelled through the combination of kinematics and state transition diagrams (STDs) that are IEC 61131 compliant. Using a mapper module within the tools, these behavioural models are **mapped** to function blocks for the automatic generation of programmable logic controller (PLC) code and virtual commissioning through OPC-UA client connectivity. A specific type of software component within the tools created for this work is the "**Product Component**" which contains the product geometry and the key product feature information described in 3.2 (Fig. 1). Although product geometry could previously be imported in the tools, there was no mechanism for enriching the information i.e. key product features/characteristics identified by the design phase. These key product features are mapped to parameters of machine component states, i.e. actuators, by the user. This link is preserved within the database of the engineering tools (**vueOne DB**, Fig. 1). Once this link exists, it is maintained as each respective component has a constant ID through its lifecycle. Thus, if a given product design changes, the machine behaviour is also modified due to the explicit **link** between data models at a fine level of granularity. Of course, it is necessary for the native product CAD format to originally have this feature "**tagged**" in a way that prevents loss during conversion (Fig. 1). At present, this issue has not been fully resolved but it is expected that the Product and Manufacturing Information (PMI) which is supported by several CAD formats would be key. The formal, explicit link between the respective PPR domains through virtual engineering tools presents the ability to i) identify whether the product features of a new variant fit into the system range through rules, ii) identify the impact of product attribute change on the resource domain through visualisation and system behaviour simulation, and iii) modification of PLC software with the confidence that it will meet requirements from the product – resource coupling. In this research, items ii) and iii) are tested in the case study.

4. Case Study

4.1. Experimental setup

The framework and approach described in Chapter 3 is applied to the battery module assembly station at the Technical University of Munich (TUM), pictured in Fig. 2. The battery cells are handled by a collaborative robot (1) mounted on a linear axis (2) in order to increase the robot range. The feeding line (3) houses battery module components. The battery modules are assembled on a central mounting station (4). The robot is equipped with a flexible cell gripper designed using the method described in Section 3.2. The application of the methodology is explained in Section 4.2.

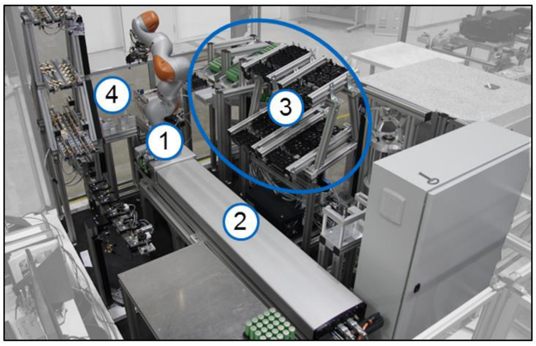

Fig. 2. Flexible and modular assembly station for battery modules.

The global requirement for the assembly station is to accommodate the assembly of battery modules for stationary energy storage and automotive applications. The different module use cases have different sets of design requirements. All components in the cell have been developed to suit a broad range of possible battery modules. In this case study, two different modules are to be assembled successively. The stationary energy storage module, product 1, consists of six cylindrical lithium-ion cells type 26650, which are arranged in a triangular configuration on a cell holder. For heat management purposes, there is a gap between the cells for air-cooling. The battery modules for the automotive industry, product 2, consist of six prismatic lithium-ion cells type PHEV1 which were developed at the TUM in the project ProLIZ. Liquid cooling of cells necessitates direct contact between the prismatic cells. The following case study demonstrates the application of the flexible component design methodology and how the introduction of product 2 is accommodated by the gripper from a mechanical flexibility and software reconfigurability perspective.

4.2. Application of component design method to the gripper

Grippers can be categorized into three flexibility domains by [27]: i) adaption to geometry and/or mass of work pieces, ii) change of functional elements, and iii) self-adaption to object-specific characteristics. Flexibility can be achieved with universal grippers that can adapt to every gripping operation and special grippers. The complexity of a gripper increases with the rise of mechanical flexibility [28], therefore its physical implementation has to be reduced and enhanced otherwise. The design methodology for flexible manufacturing system components is applied to the gripper for the system described in 4.1.

First, the general requirements list is created which focuses on avoiding cell damage and applying constant force. The product family within the context of battery modules is examined through a review of all possible cell types present in the market. Multiple criteria are researched, e.g. characteristic width of 120-173 mm for prismatic cells, 70-150 mm for pouch cells and 18-26 mm diameter for cylindrical cells. Having determined the ranges, specific process requirements are extracted, primarily oriented towards the mounting direction depending on the cell type. Cylindrical cells require uniaxial vertical mounting, while prismatic and pouch cells demand multiaxial mounting techniques. The requirements are divided into mandatory and optional criteria. Based on the requirements list, the functional decomposition is executed leading to the identification of functions such as gripper adaption to different cell geometries. Operating principles for each function were collected, for this use case, multipoint jaws and adjustable vacuum cups are selected. Two concepts were designed based on the aforementioned operating principles.

Both concepts were evaluated using a utility analysis based on the requirements list. The gripper equipped with multipoint jaws was excluded from the mechanical construction because of its inability to grip pouch cells in the sealed area, which is needed for specific handling situations. Applying the Product-Process mapping on the mechanical design of the gripper, three vacuum cups were selected enabling the handling of three round cells simultaneously, enhancing process efficiency. Moreover, the handling of pouch and prismatic hard case cells was ensured due to the extended gripping surface.

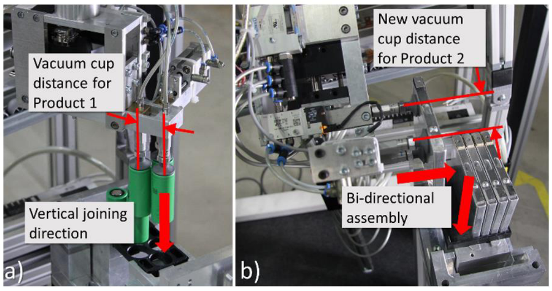

Fig. 3.(a) Gripper behaviour for product 1 and (b) new gripper behaviour achieved through software reconfiguration via engineering tool integration.

The final design consists of a fixed vacuum cup, a vacuum cup on a pneumatically driven linear axis, and a vacuum cup on a programmable electrically driven linear axis. The electrical axis contains a JUNG QuickPos® linear motor, actuated by a FAULHABER motion controller. A serial RS232-interface is used to communicate the target value to the linear motor. To ensure the handling of cells within the identified dimension range, the distance between the cups can be varied between 21.5 mm and 71.5 mm.

4.3. Mechanical flexibility

Due to the three replaceable vacuum cups, the gripper possesses adequate mechanical flexibility for the product family. Handling of cylindrical batteries is achieved through gripping centrally at the top with a distance of 29.5 mm between the cups, whereby three cells can be processed simultaneously (Fig. 3a). Cells for product 1 are picked and placed with a vertical motion. The prismatic cells of product 2 are gripped at the face with the largest surface area. The three vacuum suckers are reoriented at equal distances from the center of mass of the cell, resulting in a distance of 61.5 mm between the cups. Due to the different cooling principle of product 2, the production process also has to be changed: the vertical joining is transferred to a bi-directional joining, composed of a vertical movement, followed by horizontally joining the cells to achieve contact between them (Fig. 3b). Note that the bi-directional nature of the process is largely handled by the robot, the handling process itself is enabled by the gripper's flexible design. The design method has synthesized a broad spectrum of product and process features/characteristics into a single efficient design. The software reconfiguration necessary for the introduction of the new product is described in the following section.

4.4. Software reconfiguration

The initial conditions of the virtual model in the engineering tools are aligned to those sets of behaviours matching the requirements of product 1, e.g. the spacing between the vacuum cups of the gripper. When the production is now changed from a battery module of type 1 to type 2, new code needs to be uploaded to the PLC . Therefore a reconfiguration of the software is required due to the different requirements of product 2 compared to product 1: the vaccum cups need to change their positions. Figure 4 illustrates how data is taken from the **source CAD** file, pulled into state behaviour of system components and control code for the **PLC** is **generated** and **deployed** for product 2.

It is envisioned that the product designer would be informed which features to annotate or tag based on a set of rules created as an output of the system component design phase decribed in 4.2. The source CAD file is converted to VRML/X3D through a convertor in the engineering tools. The **annotation** is then present in the file (typically VRML/X3D does not have support for annotations, but within the toolset this is overcome through explicit insertion). When the user creates the Product Component within the vueOne toolset, the tool parses the **VRML**/X3D file for "tagged" features which then formally form part of the **Product Component** data model. Once the product feature information is within the Product Component data model, it is accessible by the **STD** of any controllable component i.e. actuator, in the engineering tool (**vueOne DB**, Fig. 4).

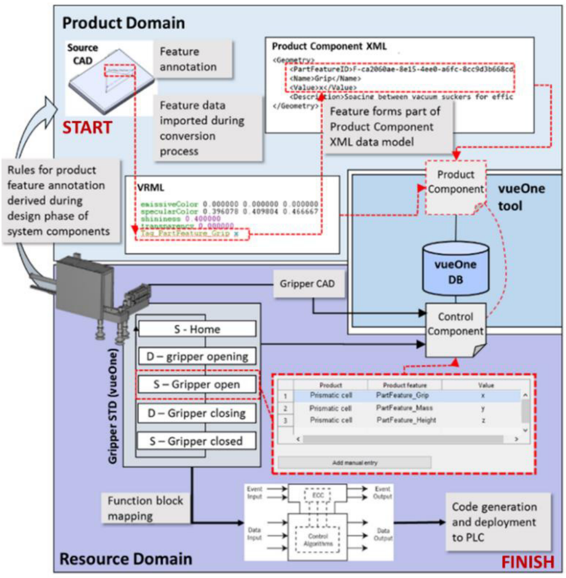

Fig. 4 Workflow for capturing product feature information and mapping to gripper behaviour. Red dashed lines indicate new workflow developed through this work, while black lines correspond to existing tool capability.

When the user imports the Product Component data model for product 2 into the virtual system, the mappings between product 1 and the STD are replaced. The user must then navigate to the gripper state associated with gripping and access product features of product 2. "PartFeature_Grip" is selected which has a value of 61.5mm. Now, an explicit link has been formed between the state of the gripper and the product feature. If the feature is changed in the VRML/X3D, the machine behaviour changes as well. This explicit mapping facilitates more rapid product and process validation, as well as system reconfiguration.

4.5. Evaluation

The case study has demonstrated how the integration between the PPR domains supports the design and reconfiguration phases of an assembly system. The approach in this study has successfully demonstrated that the gripper has sufficient flexibility to handle both cylindrical and prismatic cells with small modifications to the software. Using the methodology, the complexity of the gripper's design has been limited while still providing the necessary degree of flexibility. However, the analysis was focused on gripper design, and therefore a predefined perspective was imposed. Alternative processes may require a different set of product/process parameters to be considered. This could result in an extensive approach to system design to ensure sufficient flexibility.

Classically, modifying the behaviour of drives in an industrial application would be done on the human machine interface or through a new program on the PLC, and there would be either a very limited or no link to product data. The vision of Industry 4.0 is, in part, one of data integration. In this work, this has been achieved through the use of virtual engineering tools which integrate i) the physical world with the associated digital model, and ii) key product characteristics with machine component behaviour. The former further demonstrates the importance of virtual engineering, while the latter forms a key contribution of this work. However, some manual steps still remain. Although many CAD formats support PMI i.e. ISO 10303 STEP, ISO 14306:2012 JT, standards associated with how such information should be described do not extend into the domain of product assembly. For example, ASME Y14.41 focuses on the presentation of geometrical dimensioning and tolerancing data. Standards associated with defining assembly processes i.e. VDI 2860, are typically not present within CAD software. This results in inconsistent descriptions of tagged features and thus conventional conversion software would be unable to identify key information. This problem could potentially be overcome through the use of Semantic Web Technologies, where meaning concerning the nature of a tagged feature is preserved. Alternatively, integration between CAD tools and vueOne could be achieved through a software interface that writes PMI data directly to the database.

5. Conclusion and Further Work

The aim of this work was to demonstrate how challenges associated with reduced product lifecycles and increasing product variety, particularly within the context of batteries, could be overcome. The authors proposed a PPR framework which considered potential product variants to instill mechanical flexibility into manufacturing system components. On creation of the physical system, future product design environments would have rules which supported the tagging of appropriate product data. Virtual engineering tools then integrate digital product data to digital representations of the physical system. This facilitates pre-validated software reconfiguration realising increased manufacturing responsiveness with reduced risk. The framework has been expanded to an approach that has successfully demonstrated new product introduction on an assembly system. This work demonstrates a mechanism to achieve this through the design and (re)engineering lifecycles of products and systems. Future work includes improved integration between source CAD and virtual engineering tools for manufacturing systems, and further validation of the method associated with design of flexible system components.

Acknowledgements

The authors gratefully acknowledge the support of the Bavarian Ministry of Economic Affairs and Media, Energy and Technology through the “EEBatt” project, Innovate UK through the AMPLiFII project (ref: 102490), and UK EPSRC through KDCM (ref: EP/K018191/1) and iCASE PhD studentship (ref: 101980) for the funding of our research.

References

[1] Thiel C, Perujo A, Mercier A (2010) Cost and CO2 aspects of future vehicle options in Europe under new energy policy scenarios. *Energy Policy* 38(11):7142–51.

[2] (2009) *Transport, energy and CO2: Moving toward sustainability*. OECD IEA, Paris.

[3] Barkenbus J (2009) Our electric automotive future: CO2 savings through a disruptive technology. *Policy and Society* 27(4):399–410.

[4] Garcia-Valle R, (Ed.) (2013) *Electric vehicle integration into modern power networks*. Springer, New York.

[5] Berry WL, Cooper MC (1999) Manufacturing flexibility: Methods for measuring the impact of product variety on performance in process industries. *Journal of Operations Management* 17(2):163–78.

[6] Chryssolouris G, Mavrikios D, Papakostas N, Mourtzis D, Michalos G, Georgoulias K (2009) Digital manufacturing: History, perspectives, and outlook. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 223(5):451–62.

[7] Wöhlke G, Schiller E Digital planning validation in automotive industry. *Proceedings of the IFIP WG 5.7 Working Conference on Human Aspects in Production Management*.

[8] Maropoulos PG, Ceglarek D (2010) Design verification and validation in product lifecycle. *CIRP Annals - Manufacturing Technology* 59(2):740–59.

[9] Park CM, Bajimaya SM, Park SC, Wang GN, Kwak JG, (Eds.) (2006) *Development of Virtual Simulator for Visual Validation of PLC Program*. IEEE, Piscataway, NJ.

[10] Baqar Raza M, Harrison R (2011) Design, Development & Implementation Of Ontological Knowledge Based System For Automotive Assembly Lines. *IJDKP* 1(5):21–40.

[11] Conti JP (2008) Getting connected. *Engineering & Technology* 3(12):68–71.

[12] ElMaraghy HA, (Ed.) (2009) *Changeable and Reconfigurable Manufacturing Systems*. Springer London, London.

[13] Koren Y (2010) *The global manufacturing revolution: Product-process-business integration and reconfigurable systems*. Wiley, Hoboken, N.J.

[14] Koren Y, Shpitalni M (2010) Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems* 29(4):130–41.

[15] Wiendahl H-P, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl H-H, Duffie N, Brieke M (2007) Changeable Manufacturing - Classification, Design and Operation. *CIRP Annals - Manufacturing Technology* 56(2):783–809.

[16] Szepesi R, Ciocârle H An Overview on Software Reconfiguration. *Theory and Applications of Mathematics & Computer Science* 2011(1):74–9.

[17] Dashchenko AI, (Ed.) (2007) *Reconfigurable Manufacturing Systems and Transformable Factories: 21st Century Technologies*. Springer, Dordrecht.

[18] Chirn J-L, McFarlane DC (2000) A holonic component-based approach to reconfigurable manufacturing control architecture. in Tjoa AM, (Ed.). *Proceedings / 11th International Workshop on Database and Expert Systems Applications: 4 - 8 September, 2000, Greenwich, London, United Kingdom ; [workshop papers]*. IEEE Computer Soc. Los Alamitos, Calif., pp. 219–223.

[19] Ahmad M, Ahmad B, Harrison R, Alkan B, Vera D, Meredith J, Bindel A (2016) A Framework for Automatically Realizing Assembly Sequence Changes in a Virtual Manufacturing Environment. *Procedia CIRP* 50:129–34.

[20] Ferrer BR, Ahmad B, Lobov A, Vera DA, Lastra JLM, Harrison R (2015) An approach for knowledge-driven product, process and resource mappings for assembly automation. in Jia Q-S, (Ed.). *2015 IEEE International Conference on Automation Science and Engineering (CASE): 24 - 28 Aug. 2015, Gothenburg, Sweden*. IEEE. Piscataway, NJ, pp. 1104–1109.

[21] Mehrabi MG, Ulsoy A, Koren Y (2000) Reconfigurable manufacturing systems and their enabling technologies. *IJMTM* 1(1):114.

[22] Zoitl A, Sunder C, Terzic I (2006) Dynamic reconfiguration of distributed control applications with reconfiguration services based on IEC 61499. in Mařik V, (Ed.). *IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and its Applications: DIS 2006 ; 15 - 16 June 2006, Prague, Czech Republic*. IEEE. Piscataway, NJ, pp. 109–114.

[23] Thramboulidis K (2013) IEC 61499 vs. 61131: A Comparison Based on Misperceptions. *JSEA* 06(08):405–15.

[24] Cardin M-A (2014) Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework. *J. Mech. Des.* 136(1):11005.

[25] Tolio T (2009) *Design of Flexible Production Systems*. Springer Berlin Heidelberg, Berlin, Heidelberg.

[26] Harrison R, Vera D, Ahmad B (2016) Engineering Methods and Tools for Cyber–Physical Automation Systems. *Proc. IEEE* 104(5):973–85.

[27] Heisel U, Willmer R (1992) *Multifunktionale Greifwerkzeuge für die flexible Montage*. Universität Stuttgart.

[28] Bartenschlager J, Hebel H, Schmidt G (1998) *Handhabungstechnik mit Robotertechnik: Funktion, Arbeitsweise, Programmierung*. Vieweg+Teubner Verlag, Wiesbaden, s.l.