Omega 000 (2017) 1–16

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

An integrated framework for design, management and operation of reconfigurable assembly systems

Massimo Manzini [a,*], Johannes Unglert [b], Dávid Gyulai [c,d], Marcello Colledani [a], Juan Manuel Jauregui-Becker [b], László Monostori [c,d], Marcello Urgo [a]

[a] Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy
[b] Department of Design, Production and Management, University of Twente, Enschede, The Netherlands
[c] Fraunhofer Project Center PMI, Institute for Computer Science and Control, Hungarian Academy of Sciences, Budapest, Hungary
[d] Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics, Budapest, Hungary

ARTICLE INFO

Article history:
Received 16 December 2016
Accepted 9 August 2017
Available online xxx

Keywords:
Reconfiguration
Manufacturing
Design
Layout
Assembly
Uncertain market

ABSTRACT

Manufacturing has to cope with the continuously increasing variety of products, change of volumes and shortening product life cycles. These trends also affect the automotive sector: the frequent introduction of new models, materials and assembly technologies put the suppliers of *make-to-order* parts under pressure. In this context, the design of assembly systems and their management are of paramount importance for the companies' competitiveness. In this paper, we propose an approach for the design and reconfiguration of modular assembly systems through the integration of different computational tools addressing the design of the system, the optimization of the layout, the planning of reconfiguration actions as well as production planning. Integrating these computational tools and iterating through the resulting workflow and feedback allow to consider the outcomes and dependencies of alternative decision sequences holistically with the objective of an effective and efficient approach to production system design and management. The viability of the approach is demonstrated through the application to an automotive case study.

1. Introduction and motivation

Throughout the last decade, manufacturing industry has been confronted with an increasing variety of products and the consequent reduction of production volumes, together with the continuous shortening of products' life cycle [13]. In this context, the design of manufacturing systems becomes a complex task that entails manufacturing strategy decisions, has long-term impacts and involves a major commitment of financial resources [48]. Hence, manufacturing systems must be able to smoothly and rapidly adapt to the fast evolving market dynamics. Different system paradigms have been proposed to efficiently and effectively adapt to the market dynamics, e.g. flexibility [19] and reconfigurability [14,27]. These paradigms implement specific technological features such as modularity and changeability, to enable modifications of the production systems in response to the needs of the market [52]. Moreover, the concept of *co-evolution* of products, processes and production systems has been identified as a key factor in companies to manage strategically and operationally the propagation of engineering changes, and to gain competitive advantage from the resulting market and regulatory dynamics [47,49].

In this paper, we focus the attention on tier-one automotive suppliers of car-body assemblies. *Original Equipment Manufacturers* (*OEMs*) typically rely on this class of suppliers to produce spare parts for the aftermarket. Nevertheless, as *OEMs* are moving towards an increasing variety of models, suppliers are also involved in the production of parts during the ramp-up of new models, as well as in complementing the *OEMs* production capacity for high-volume car models to help managing demand peaks. Besides the high variety of models characterizing these market segments, the automotive industry is also experiencing a continuous technological evolution. To remain competitive, the suppliers have to match this evolution in the design and management of their production systems, also providing the capability to integrate new technologies into the system. In addition, suppliers have very limited degrees of freedom, since *OEMs* decide about the design of the products, the associated assembly technologies and, in many cases, also the equipment that must be used. Hence, the only strategic factors the suppliers can exploit are the design and management of their production systems to quickly adapt to the *OEMs* requirements.

* Corresponding author.
E-mail address: massimo.manzini@polimi.it (M. Manzini).

http://dx.doi.org/10.1016/j.omega.2017.08.008

Consequently, suitable design and operation policies must be applied to ensure that the high variety of products with low, medium and high demand can be constantly satisfied.

As a response to these challenges, we propose an integrated design approach for batch assembly systems, organized in a cellular layout. The variety of products, assembly technologies and processes to be considered in the design of such systems results in a broad range of potential system designs. The proposed integrated approach aims to help managing this complexity through a holistic method to design evaluation. The approach integrates four computational tools to support (i) the definition of the system's configuration, (ii) the selection of the cell's detailed layout and assembly process' options, (iii) the production planning and (iv) the reconfiguration steps that have to be taken at certain moments. The four complementary tools aim to support the design of assembly systems and their managing policies. Using them in an integrated way enables to increase the level of details incrementally, and gain additional knowledge about the system. Moreover, feedback loops are implemented between the computational tools, to improve the design or manage possible infeasibility. The integration of the decision-support tools aims at providing a robust solution able to cope with the co-evolution of the system together with the products and the production technologies. In this fashion, the configuration, layout planning and reconfiguration of the system consider long-term decisions, while the planning of production is based on the short-term horizon.

The paper is organized as follows: Section 2 describes the state-of-the-art in the research areas related to the integrated approach, Section 3 addresses the overall formulation and notation, Section 4 provides the structure of the integrated design approach while Section 5 presents the computational tools and their interplay in detail. Section 6 illustrates the application to a case representative for the automotive industry, while Section 7 provides a summary of the approach and future research directions.

2. Design and management frameworks: state-of-the-art

The approach we present in this paper is based on the integration of different computational tools to support a wide range of design and planning decisions throughout the life cycle of production systems. As highlighted by Dolgui et al. [3,23], integrated decision support methods can offer significant benefits over isolated ones to solve complex problems that cannot be handled by a single model. Hence, the approach allows to determine and connect solutions for the emerging sub-problems on different levels of detail to avoid sub-optimal decisions. Due to the modular implementation of the proposed approach, the state-of-the-art analysis considers literature dealing with system configuration, layout, management and integration of these aspects.

Cellular manufacturing systems as means to achieve manufacturing flexibility has been a subject for research already for a long time [46]. Even though advances are documented in more recent publications such as [41], a number of challenges in the field are still present today. One aspect that has been identified as vital for successfully applying the cellular concept is the consideration of its dynamics in design models, as described by Goldengorin et al. [15]. The authors conclude that, since the product mix changes over time, also the cell's layout must be adjusted periodically to obtain systems, which are robust with regard to a changing product mix, or dynamic, realizing smooth changes of the system's structure.

Hu et al. [22] and Koren and Shpitalni [28] suggest to combine the layout and production planning of systems to match the system structure with the customers' demands. Nevertheless, they argue that this topic so far received little attention by researchers. Li et al. [32] argue that the throughput of the system is usually determined by considering the bottleneck process only, without considering the applied production sequence. Moreover, setups and changeovers seem to be rarely considered during the design phase of the line: Battini et al. [4], Boysen et al. [6] and Nazarian et al. [39] expose that the link with production planning and the resulting actual batch sizes and changeovers appears to be rather loose. An integrated methodology focusing on the automotive assembly process is presented by Ceglarek et al. [7], where the authors consider the configuration of a *remote laser welding* assembly line together with the production process and task sequencing. The approach focuses on the design and high level performance evaluation, without taking into account the reconfiguration of the system. Matta et al. [34] describe an approach to design reconfigurable systems, estimating the system's ramp-up performances and also considering the reconfiguration option to increase or decrease the system's capacity. In addition, the authors generate a robust solution by applying a Markov Decision Process to consider multiple time periods. An approach that takes into account the design of multi-product flexible transfer lines and its reconfiguration is presented by Tolio and Urgo [50]. In particular, the configuration phase consists of assigning operations and equipment components to selected stations, while during the reconfiguration phase, the system's equipment components are rearranged to match the changed requirements.

Considering the main design and management aspects in the scope of this paper, an interesting work is presented by Hu et al. [22], where multiple approaches to designing assembly systems are reviewed and summarized, taking into account reconfigurability, flexibility and co-evolution aspects. Even though all the cited approaches cope with the overall configuration and management problem by integrating support methods on different levels, the information transferred between the models mostly flows into one direction. Seizing the opportunity to review and improve higher-level decisions based on the more detailed solutions resulting from lower-level support approaches is not considered.

Delorme et al. [11] state that assembly line configuration problem is a widely studied, relevant industrial topic involving a set of various optimization sub-problems. Guschinskaya et al. [16] consider the configuration problem for assembly systems without buffers by using a heuristic multi-step approach. They face the problem of grouping operations in several stations and minimizing the total equipment cost. They propose partitioning the layout design process into several steps and introducing technology constraints and precedence relations sequentially. All manufacturing operations are considered with a fixed assignment of the machine tools to spindles and without taking into account alternative machining processes. The extension of this work is presented by Makssoud et al. [33], where also reconfiguration actions are considered. In both cases, the volumes to be produced and also the processing times are treated as deterministic parameters. A similar configuration problem is faced in [17] by using a three-step genetic approach. Other approaches focus on the robust design [42], balancing [9] and scheduling [26] of assembly lines, considering the flexibility of the resources and uncertainty of the key parameters. Another stream of research is represented by Heilala et al. [20] where an approach combining design and simulation for modular assembly systems is presented, with the objective of minimizing the total cost of ownership. This approach tries to cope with the overall management problem by considering a specific class of assembly systems, but it does not offer the opportunity to chose between alternative technology solutions in terms of type of equipment and task sequence. An approach that considers different equipment alternatives is presented by Michalos et al. [37]. In this case, the design approach consists of two phases: first, the equipment components are selected for the system and, subsequently, arranged to form the assembly line configuration using an optimization algorithm.