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Future trends in management and operation of assembly systems: from customized assembly systems to cyber-physical systems

1. Introduction

Some of the most influential management concepts have their origin in the organization of assembly systems: from Henry Ford’s assembly lines and the concept of mass production, to the more recent Toyota Production System and the principles of lean manufacturing. Currently, assembly systems experience dramatic changes imposed by altering market conditions and profound shifts in existing technologies. Mass customization is one of the important current trends. Modern markets demand customized products at low cost that feature, e.g., short product life cycles, short time to market, and high reliability of deliveries. The ability to offer customized products at prices comparable to that of standard products is defined as mass customization [6,16]. Mass customization requires rethinking of the processes along the whole supply chain, but the need for change is especially pronounced in design and management of assembly systems. Theoretical analysis and mathematical models have become essential as never before to address the challenges of mass customization that can be summarized in the following two points:

- Assembly processes should become more flexible, adaptable, and agile to cope with increased product variety and market volatility. This requirement concerns equipment, personnel, organization of production and decision processes. For instance, product customization shifts product tagging, i.e., assignment of a particular workpiece to a specific customer order, earlier into the production process [20]. As a consequence, without fast and efficient correction in case of failures and disturbances, tremendous increase of overhead capacities, deemed as “hidden factory”, would be required in order to keep rework times short and keep up with promised delivery dates. This calls for zero-fault manufacturing and robust planning coupled with real-time replanning approaches.
- Market volatility, decreased product life times and increased complexity and interdependency of production processes require integrated planning and management of assembly systems together with other functions of the enterprise. For example, to shorten the time to market, companies rely on concurrent engineering and digital representation of manufacturing processes – this is an example of a vertical integration, which is integration along the time line. Digital twins of production factories and assembly systems help to validate manufacturability of new products across all the required processes and to evaluate production cost already in the early steps of product design. The integration takes place not only vertically, but also horizontally, across business functions, such as logistics, assembly, manufacturing of components, maintenance and postprocessing.

The outlined challenges call for a profound change in managerial approaches to assembly systems. This special issue offers novel planning approaches for managers that improve the performance of modern assembly systems and increase their flexibility, adaptability, and agility.

In the following, we introduce the articles of this special issue in Section 2. We conclude with a discussion of future trends in assembly systems and research perspectives in Section 3.

2. Overview of the contributions in this special issue

The idea of this special issue is to attract attention of researchers and practitioners to the current significant changes of the focus of assembly systems and to discuss new challenges in this field as well as new optimization techniques to address them. In this section, we summarize the contribution of each paper to this overall goal.

Abbas and ElMaraghy [1] as well as Manzini, Unglert, Gyulai, Colledani, Becker, Monostori and Urgo [14] propose integrated planning approaches for adaptable assembly systems. These are foresightful approaches, since they consider reconfiguration cost of assembly systems due to possible future shifts in demand.

Abbas and ElMaraghy [1] develop an integrated planning approach for reconfigurable robotic assembly systems. They argue for a simultaneous development of products and of manufacturing systems for their production in order to address reconfiguration costs of assembly systems and possible product modifications already in the design stage, this methodology is called co-platforming. For instance, in case of highly variable product demand and medium differences between product families, manufacturing and investment cost may be lower if we design an assembly system with a small number of general robots instead of a large number of dedicated specialized machines. The developed integrated planning approach consists of three stages: mapping of assembly machine candidates to products and their components, selection of the assembly machines and arrangement of the assembly machines into production stages to perform assembly opera-

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tions in a technologically feasible order. The developed methodology will help managers to introduce new products while keeping manufacturing and investment costs low.

Manzini, Unglert, Gyulai, Colledani, Becker, Monostori and Urgo [14] design an integrated planning approach for batch assembly systems organized in a cellular layout. The authors specifically target reconfigurable cell architecture, which adapts to changes in demand. Their integrated planning includes decisions on system configuration – such as the number of cells, assignment of products and production technologies to cells, and routing of products among cells – selection of cell layout including task sequencing, as well as production planning to satisfy customer orders with given delivery dates. The authors decompose the overall planning problem into three sub-problems, which are related with feedback loops. The feedback loops enforce interdependencies between the sub-problems and help overcome possible infeasibilities due to decomposition.

As discussed above, modern assembly systems are particularly prone to disturbances because of high product variety and volatility of the demand. Ben-Ammar, Dolgui and Wu [3] as well as Pereira and Álvarez-Miranda [15] develop planning approaches that can deal with uncertain information.

Ben-Ammar, Dolgui and Wu [3] determine when to start production of components at the last level of the bill of materials to minimize expected inventory and backlogging cost given uncertain lead times. Customer demand is considered as known. Lead times are hard to predict especially in assembly-to-order systems, when minor disruptions, such as machine breakdowns, may cause significant delays. The authors propose a new generalized model for multi-level assembly systems with a number of levels greater than two. Such assembly systems are common for highly complex products. First, Ben-Ammar, Dolgui and Wu reduce the solution space by decomposing the multi-level assembly system into several linear supply chains. Then, the authors use a novel branch-and-bound algorithm to compute good quality solutions in short time.

Pereira and Álvarez-Miranda [15] examine a robustified version of the assembly line balancing problem in which task durations are uncertain. Sources of uncertainty are manifold at modern assembly lines, especially in case of manually performed processes. Moreover, since planning of assembly lines usually performs calculations for “nominal” (“typical”) workpieces with averaged processing times, actual processing times of individual workpieces may deviate from the planned times, especially in case of customized products. The authors develop well-performing exact and heuristic solution approaches that leverage specifics of the problem structure. In their extended computational experiments, Pereira and Álvarez-Miranda show that if uncertainty levels are moderate, the assembly lines can be robustified at relatively small cost (a low number of additional stations).

Flexible, adaptable assembly systems require flexible planning and modeling approaches that can be easily adapted to changes in the constraint set. Bukchin and Raviv [5] favor the integration of model building and constraint-programming (CP). The authors developed new mathematical models for various optimization problems dealing with task assignment in assembly lines such as simple assembly line balancing problems (SALBP-1 and -2), task assignment in U-lines, and the joint problem of task assignment and equipment selection, sometimes referred to as the assembly line design problem. Since CP enriches successfully several commercial or open-source software packages, we believe that these models will be helpful for managers in modeling new optimization problems that will constantly appear in the evolving assembly environment.

A basic question of current research on mass customization is how to produce customized products at low manufacturing cost. Taube and Minner [17] favor for resequencing of workpieces in the automotive-parts production. Product customization and short promised delivery dates enforce tagging early in the production process. For instance, in the case of a tier-one automotive manufacturer, products have to be delivered just-in-time and just-in-sequence to the original equipment manufacturer, whereas information on the required product sequence comes shortly before the start of production. By adopting a favorable workpiece sequence at the beginning of production and restoring the required product sequence at the end, managers can economize on setup cost (e.g., by minimizing the number of switches between different product options), level the material consumption, and balance the workload. As a result, manufacturing cost decrease. Taube and Minner present effective mixed-integer models for product resequencing performed with a so-called mix banks technology (or several queues of limited capacity) and apply a limited look-ahead heuristic to solve the problem for large instances of practically relevant size. The authors examine resequencing in detailed computational experiments. In their calculation example, resequencing resulted in significant cost savings of several million euros.

Several contributions discuss planning approaches for manual assembly systems, since currently assembly has the lowest levels of automation within the production process [9,10]. Most likely, manual operations will still exist in final assemblies in the future because of high expectations towards flexibility at this stage of production.

Bai, Tang, Zhang and Santibanez-Gonzalez [2] draw attention to the presence of learning effects in repetitive productions. The authors study a permutation flowshop scheduling problem with release dates and learning effects, i.e., scheduling workpieces in an un paced assembly line with infinite buffers between stations where the processing order of workpieces remains the same in each station. The authors point out that the studied classic scheduling objective functions – minimization of the makespan, total completion time, and total quadratic completion time – can be used to model and optimize key decision criteria, such as energy consumption, machine load, work-in-process, and inventory cost. The paper proposes an exact branch-and-bound algorithm that successfully solves small problem instances with up to 12 workpieces. For large instances of practice-relevant size, the authors formulate a shortest processing time available heuristic (SPTA), which they prove to be asymptotically optimal in case of independently identically distributed (base) processing times. Since the studied dynamics (functions) of learning effects are quite general, we believe that the developed planning approaches will be useful in scheduling in un paced assembly lines in various industrial environments.

Tiacci and Mimmi [18] develop a new methodological approach to design mixed-product asynchronous assembly lines in compliance with ergonomic legislation. Their study shows that the improvement of working conditions for operators respecting international ergonomic norms can be achieved with very limited additional cost. The practitioners can use the developed approaches to reduce risk of musculoskeletal disorders frequently affecting the well-being and health of assembly operators. The use of such approaches will help to attain better and fairer workload sharing among operators and to improve the system sustainability.

3. Further trends and research perspectives

The particular emphasis of this special issue was placed on the mass customization in assembly systems. We believe that the selected papers not only offer valuable insights on different facets of this current trend, but also pave the way for future developments. Indeed, the presented studies show the importance of future research to make the assembly systems more flexible, adaptable and agile as well as the need for integrating the decision making pro-
cess horizontally and vertically. The results included in this special issue will help researchers to develop tighter models for analyzing human performances and human workloads in assembly systems, to model more flexible work assignment including worksharing, to exploit new assembly layouts and new design solutions while taking into account the uncertainty of volatile markets.

In addition to the challenges related to changing customer requirements and market conditions, in particular to mass customization discussed in Section 1, future research studies have to address challenges posed by emerging technologies. The importance of these technological changes has grown to the point where most experts employ the term of the forth industrial revolution (so-called Industry 4.0) and predict its ramifications to be comparable to those of mechanization, electrification and automation of manufacturing processes [4,7]. Industry 4.0 is closely connected with the digitalization of industrial processes and equipment, cyber-physical systems or the Internet of things, and the capability of real-time big-data processing. These new technologies have started to change the assembly systems and new organizational forms of assembly processes have emerged (see, e.g., [11,12]).

New technologies open new opportunities, but also bring additional challenges to the assembly systems to unleash these opportunities (cf. [8,13]):

- Future planning and control approaches should orchestrate interaction of intelligent units, such as cooperation and communication rules, flexible delegation of decision authority. Machines evolve to self-regulated systems capable to adapt to new tasks, to perform self-diagnostics and self-maintenance. Moreover, decreasing cost and refinement of sensors as well as networking and cloud technologies will enable to bestow even the smallest components of the assembly system, such as a workpiece or a machining tool, with decision autonomy. Therefore, appropriate planning and control methodologies that support decentralized autonomous decision making as well as set up flexible cooperation rules and efficient information exchange policies between components of the assembly system are required.

- Future planning and control approaches should exploit large amount of data in real time. With new technologies, an extensive amount and variety of data becomes available in real-time, asking for efficient real-time replanning techniques. Thereby, data analytics and artificial intelligence enable the analysis and extraction of useful information from terabytes of available data, as well as continuous learning about correlations and cause-and-effect relationships. Operations research disposes a large arsenal of methods on how to select the best possible actions given the known system state. Exploiting synergies of methodologies of these disciplines is necessary for effective planning and control of highly complex assembly systems of the future.

- New technologies may require a close collaboration between workers and machines, such as robots or other artificial intelligence units. Collaborative robots, or so-called cobots, is an example of such collaborative technology. Cobots can work hand-in-hand with workers, so that no safety barriers for spatial separation of cobots and humans are required and time and cost for assembly system redesign are of minor relevance. The use of cobots offers the possibility to combine flexibility of workers with advantages of machines, for instance, in handling of weights and precision tasks and, thus, leads to better ergonomically designed workplaces. The Assembly magazine’s readership survey State of the Profession, reports that 31% of respondents expect to deploy cobots within the next year [19]. Augmented reality and adaptable workstations are further examples of collaborative technology. Smart glasses, intelligent workstations and equipment can assist the operators, interact with them and provide instructions in real-time. Exoskeletons and other wearable technologies will increase the well-being of the operators and enhance their capabilities. Currently robots and computers cannot always interpret and predict the behavior of humans, therefore, deep research studies are needed to achieve high productivity of human-machine systems and to provide human operators a safe working environment with low psychosocial risks.

The complexity and heterogeneity of future assembly systems call for a close interaction between researchers and practitioners. Future research will require a fruitful interdisciplinary collaboration of the specialists in robotics, computer science, ergonomics, operation research and management to solve complex and rapidly evolving problems.

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