Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 63 (2017) 459 – 464

www.elsevier.com/locate/procedia

50th CIRP Conference on Manufacturing Systems (CIRP-CMS 2017)

# Scheduling and operator control in reconfigurable assembly systems

Dávid Gyulai[a,b,*], Botond Kádár[a], László Monostori[a,b]

[a]*Fraunhofer Project Center at Institute of Computer Science and Control, Hungarian Academy of Sciences, Kende str. 13-17, H-1111 Budapest, Hungary*
[b]*Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics, Egry J. str. 1, H-1111 Budapest, Hungary*

[*] Corresponding author. Tel.: +36-1-279-6181; fax: +36-1-466-7503. *E-mail address:* david.gyulai@sztaki.mta.hu

**Abstract**

Pushed by the recent market trends, companies need to adapt to changeable demands, regarding both mix and volume, in order to keep their competitiveness. Modular and reconfigurable assembly systems offer an efficient solution to these changes, providing economies of scale and also economies of scope. In the previous works of the authors, novel methods were presented to solve strategic level system configuration, and tactical mid-term production planning problems related to modular, reconfigurable assembly systems. The paper relies on these results, and aims at extending the previously proposed planning hierarchy on the short-term, daily production scheduling. The objective is to minimize the total operator headcount, considering the production lot sizes calculated on a higher, planning level on a working shift basis. The analyzed scheduling problem requires novel models, as important constraints in the scheduling problem are the reconfigurations consuming time as well as resources. In the paper, constraint programming and metaheuristics models are formulated and compared, resulting in production schedules that specify the production sequences, and the operator allocations. Conclusively, the operator controls can be also obtained from the results, specifying a work plan and tasks for a given operator within a working shift. The proposed methods are compared by using real industrial problem instances.

Peer-review under responsibility of the scientific committee of The 50th CIRP Conference on Manufacturing Systems
*Keywords:* reconfiguration; scheduling; assembly

## 1. Introduction and motivation

The greatest recent challenge in production management is to match production capacities with the market conditions, characterized by increasing complexity in product variety, as well as diversity in volume. This leads to the fragmentation of orders that are to be handled by careful production planning in order to keep the internal efficiency of the company at a desired level, and stay competitive in the market. Reconfigurable production systems provide a cost-efficient option to match production with fragmented order stream, by offering changeable structure and scalable capacity. Although their efficiency is proven for years now, their industrial application requires special production planning and control approaches to utilize their structural and technological advantages. These approaches must consider the ever changing structure of the applied reconfigurable system's structure, in order to determine proper production plans and assign orders to capacities while keeping the target level of the production performance indicators. In the paper, a two-level production planning and control methodology is proposed to calculate cost-optimal production plans and the corresponding schedules for modular reconfigurable assembly systems.

### *1.1. Modular reconfigurable assembly systems*

In product variety management, changeability of the production systems is a key concept towards efficient synchronization of production processes and customer orders' stream [1]. Changeability is an umbrella concept, encompassing key enablers, among which modularity plays an important role both on the logical and the physical system level. On the latter, the concept stands for the application of so-called *plug and produce* production resources with standardized design and interfaces, as well as with the capability of autonomous operation [2]. Focusing on the assembly processes, modular configuration enables organizations to adjust the physical structure of the system to the assembly processes with low effort considering both time and resources [3–5]. Besides, in planning and control of assembly systems, balancing the operators' workload is of crucial importance to keep the efficiency [6]. Though the literature of reconfigurable production and assembly systems is rather extended, there are a few papers only with the special focus on the production planning and scheduling of these systems [7–9]. Among this limited set of papers, fast reconfigurable assembly systems with modular resource constraints in planning and scheduling are not considered, therefore, the paper and the presented research is aimed at filling this gap by introducing a

2212-8271 
Peer-review under responsibility of the scientific committee of The 50th CIRP Conference on Manufacturing Systems
doi:10.1016/j.procir.2017.03.082

two level capacity management framework for these systems.

### 1.2. Operation of modular assembly systems

In the paper, a modular, reconfigurable assembly system is under investigation, which consists of lightweight, *plug and produce* assembly workstations (modules). Each module is dedicated to a single assembly process, and has standardized design including standard connectors and docking interfaces. The modules have a mobile, lightweight frame design enabling fast, short term reconfigurations. They are equipped with assembly tools that can be adjusted to perform assembly processes with different parameters (e.g. screwing torque, screw size etc.). Each of the products assembled in the system is supposed to have assembly tasks that can be performed by applying the standard modules. Therefore, the assembly process of a certain product can be split up into a sequence of standardized assembly tasks (e.g. screwing, pressing) that can be matched with the sequence of the corresponding standard assembly modules. The lines are configured manually on the shop-floor by operators, so as the mobile workstations are placed sequentially according to the successive assembly operations. The configuration is always performed based on the product type to be assembled, and the lines are reconfigured when the assembled product type is changed. The simplified operation (reconfiguration cycle) of the system is the following:

- Configuration: First, the assembly line is built-up by means of the standard modules (which are required by the actual product), by moving them next to each other according to the assembly process steps.
- Setup: The operator performs the necessary setup tasks, e.g., plugs in the air connectors, and places the necessary fixtures on the modules. The operator prepares the necessary parts required by the given assembly processes.
- Assembly: The operator assembles the products in the required volume.
- Deconfiguration: After an assembly process is finished, the operator dismantles the lines, by moving back the excess workstations to the resource pool.

The above described dynamically changing system structure enables flexible production —especially regarding the mix of products assembled—, however, it also requires flexibility in the human workforce, to be capable of performing the reconfigurations as well as the assembly processes. On the operational level of the production planning hierarchy, flexibility in human workforce means that the operators can be assigned to different tasks within their working time (production shift). Technically, this means that each operator is assigned to multiple tasks to perform within the same production shift, and the operator changes task once he/she performed the previous one. The operational level scheduling in this case stands for the operator-task assignments including the starting times of the tasks. In the following sections, the formal definition of the problem in question is provided, applying the notation summarized in Table 1. The input data of the scheduling is provided by the solution of the higher level production planning process, specifying the assembly tasks to be performed within a given time period $t \in T$, therefore, the production planning model and its solution are introduced first.

Table 1. Notation applied in the paper

| | |
|---|---|
| | *Sets* |
| $T$ | set of production time periods |
| $P$ | set of products |
| $H$ | set of operator headcounts |
| $N$ | set of orders |
| $J$ | set of modules |
| $L$ | set of lines |
| | *Parameters* |
| $t^w$ | length of a planning period |
| $t^s_p$ | setup time of product $p$ |
| $t^p_p$ | total manual processing time of product $p$ |
| $o^{max}_p$ | maximum operator headcount of product $p$ |
| $r_{jp}$ | required number of modules from type $j$ by product $p$ |
| $t_{ph}$ | cycle time of product $p$ when assembled by $h$ operators |
| $c^{op}$ | cost of an operator per period |
| $q_j$ | amount of modules from type $j$ |
| $c^h$ | inventory holding cost [cost/part/period] |
| $c^l$ | late delivery cost [cost/part/period] |
| $c_{nt}$ | deviation cost of order $n$ if executed in period $t$ |
| $v_n$ | volume of order $n$ [pcs.] |
| $t^d_n$ | due date of order $n$ |
| $p_n$ | product of order $n$ |
| $v^{min}_p$ | minimal lot size of prodct $p$ |
| | *Variables* |
| $x_{ntlh}$ | assemble order $n$ in period $t$ and line $l$ with $h$ operators |
| $r_{jlt}$ | number of modules from type $j$ required at line $l$ in period $t$ |
| $O$ | total headcount of operators |
| $t^{START}_n$ | execution start time of task $n$ |
| $t^{END}_n$ | execution end time of task $n$ |

### 1.3. Production planning problem

In the production planing model, the objective is to determine the production lot sizes $x_{ntlh}$ by matching the available capacities (human and machine) with the customer demands. The planning horizon $T$ is divided into equal length time buckets $t \in T$, and a given set of orders $n \in N$ corresponding to products $p \in P$ need to be completed. The assembly processes are performed by applying $j \in J$ different module types, each type is capable of performing a single process type. The amount of modules from each type $j$ is limited by the resource pool $q_j$. It is assumed, that the number of simultaneously operating reconfigurable lines is limited along the horizon by introducing the set of lines $l \in L$. These lines are "virtual", as they have no static parts but only composed of reconfigurable modules, however, it is supposed that they are placed on a finite set of segments on the shop floor, and each line occupies a single segment. This assumption is required to manage the machine resources in the production planning model, as the module-line assignment can be constrained in this way. Similarly to the modules, the human resource requirements are also constrained in the production planning model by introducing a set of headcounts $h \in H$ that can be applied to assemble a given product type. In the analyzed problem, skills are not considered, thus an operator can perform any assembly task. Based on the above assumptions, the production planning model is specified as follows. The production lot executions are to be determined