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Procedia CIRP 57 (2016) 445 – 450

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49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016)

Simulation-based Production Planning and Execution Control for Reconfigurable Assembly Cells

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Abstract

In order to meet the continuously changing market conditions and achieve economy of scale, a current trend in the automotive industry is the application of modular reconfigurable assembly systems. Although they offer efficient solution to meet the customers needs, the management of these systems is often a challenging issue, as the continuous advance in the assembly technology introduces new requirements in production planning and control activities. In the paper, a novel approach is introduced that enables the faster introduction of modular assembly cells in the daily production by offering a flexible platform for evaluating the system performance considering dynamic logistics and production environment. The method is aimed at evaluating different modular cell configurations with discrete-event simulation, applying automated model building and centralized simulation model control. Besides, the simulation is linked with the production and capacity planning model of the system in order to implement a cyclic workflow to plan the production and evaluate the system performance in a proactive way, before releasing the plan to the production. The method and the implemented workflow are evaluated within a real case study from the automotive industry.

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems
Keywords: reconfiguration; assembly; simulation; production planning; control

1. Introduction and motivation

Frequent changes of the production portfolio regarding both volume and mix are recent common characteristics of the automotive industry. These changes are usually resulted by the competitive market that requires continuous innovations in order to keep the existing customers and attract new ones. Car manufacturers need to be flexible in order to meet these requirements, however, this assumption is even more valid for the automotive supplier companies, whose time available for respond to the changes is even more limited than that of the end producers [1]. In most of the cases, changes in the volumes are predictable with proper forecasting, however, technological changes are more crucial as the lead time of adopting the existing production systems to the new technologies can be very long. When changing the configuration of a system to meet the new technological requirements, time, money and quality aspects are all need to be respected. These factors introduce complexity to the production system configuration task, even if flexible technology is already applied. Flexible and reconfigurable systems are designed to cope with changes of volume and mix, however, efficient management of these system besides continuously changing technologies are still complicated.

Reconfigurable production systems are capable of being adjusted to the changed volumes and product mix by altering the physical configuration of the system. These systems are often utilize the modularity, which means that standardized system elements are used for performing the selected operations. The modules are usually designed for performing a single type of operation, and their application is generally based on the actually manufactured product type. When switching the production from one product type to another, a reconfiguration is required, which means that the excess modules need to be replaced by the ones required to produce the next product. Focusing on the assembly technology, reconfigurable systems can be used efficiently to assemble products by applying modules that are specifically designed to support joining technologies [2,3]. In contrast to machining systems, a specific enabler of the systems changeability is the mobility of system components, which is necessary to reconfigure station or modules. Besides, the scalable level of automation facilitates to balance the human and machine capacities with the desired production rate [4].

Regarding the management of these systems, the co-evolution of product families and assembly systems is needed to stay competitive by maximizing the reuse of product and system modules, which ensures that the system will be capable

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems
doi:10.1016/j.procir.2016.11.077

of producing the future product types/generations [5]. Emerging problems mostly regard to the management of capacities, namely to plan the system scalability on the longer term in order to ensure cost-efficient production on the short term [6,7].

In the paper, the latter problem is analyzed, and solved by linking the simulation model of the assembly systems with the production planning model to evaluate the system performance in a proactive way. Besides, the control of the assembly cells is also solved by using the simulation model in an emulation mode, which enables the testing of different control methods even without having the physical system itself. A modular car body assembly system is analyzed from planning and control viewpoints, and a methodology is proposed to plan the production and analyze different control modes. The proposed approach is part of a step-by-step workflow, with the purpose of cost-efficient and quick revision and harmonization of the applied production system and the product portfolio. Revision in this case means the evaluation of the applied technology considering the possible future changes. In the currently analyzed reconfigurable system, technological changes can be done by changing the modules only and leaving the basis of the system unchanged.

2. Problem statement

In the following sections, the considered multi-level problem is specified by detailing the production planning and control sub-problems. Both evaluation and planning concern to a given system configuration with the corresponding assembly tasks, therefore, the main inputs are the detailed physical architecture of the assembly cells and the tasks of the products, specified with the relevant technological parameters. In the following section, the general scheme of the analyzed assembly cells is introduced.

2.1. Modular reconfigurable cell designs

As for the configuration and architecture of the assembly cells, modular reconfigurable cells are considered, whose design relies on the following scheme. The cells are the combination of static and dynamic elements, of which static elements are considered as the skeleton of the cells that are mostly responsible for material handling and accepting the changeable modules. Typical static cell elements are conveyor belts, input and output buffers as well as the fences that separate the cell from its environment. In the assembly cells, further static parts are the robots that mostly perform technological processes and also material handling tasks.

Exchangeable cell elements are the modules that typically responsible for performing different technological processes, and each module can execute a single operation type only. The modules have a common interface which ensure the compatibility between the modules and cells. The simplified procedure of a reconfiguration is as follows: before starting the operation of a certain product type, all excess modules from the selected cell are removed. The assembly instructions of the product type prescribe the exact amount and type of modules that are required for the assembly. These modules are collected from the module pool (e.g. module stock), and transferred to the cell. Next, each module are installed by physically placing it on standardized mounting interface, and plugging in the cables of the control and energy flow. Then, the cell is ready for production, after assembling the given lot form the selected product type, a new type can be assembled again after a reconfiguration.

2.2. Dynamic evaluation of design and plan alternatives

The planning and evaluation methods introduced in the paper are part of a comprehensive workflow that is defined for the design and frequent revision of modular reconfigurable assembly cells, by harmonizing the entire system configuration with the continuously changing product portfolio and customer needs. Each step of the workflow is aimed at adding more details to the system specification by utilizing the results of the preceding planning steps. As introduced in Section 2.1, the input of the dynamic evaluation is the system configuration, which is resulted by the preceding step in the workflow, and responsible for the detailed design of the assembly cells considering the technological and technical constraints and requirements. Though, the solution is technologically feasible, dynamic evaluation of the cells are necessary in order to analyze their performance when logistics objectives, realistic stochastic parameters and random events are also considered. By this way, the feasibility and reliability of the cell configuration can be decided in advance, without having the real facility.

Dynamic performance evaluation is aimed at adding novel aspects to the analysis, considering not the single cell only, but its production environment with the linked processes of the value chain. The evaluation is done by applying the discrete-event simulation model of the reconfigurable cells and the linked processes. First main input of the simulation is the description of the assembly processes that specify the processing times, routings in the cell as well as the manual processes. Other important inputs of the analysis are the production plan, whose calculation is detailed in the following section. Having the production plan specified in the analysis, the resource sharing and, therefore, the inter-cell processes can be analyzed that was not possible in the preceding steps of the workflow. The purpose of executing the dynamic evaluation is to evaluate the performance of the cells whether they can provide the desired output rate or not, and besides, to analyze the logistics performance indicator when executing a production plan in a simulation environment. By this way, feedbacks to both the preceding cell configuration steps and the production planning can be done, regarding the quality of the calculated solutions.

2.3. Production planning of modular reconfigurable cells

Production planning is responsible for matching the order stream with the available capacities considering both the static reconfigurable cells and the changeable modules that are shared among the cells. The notation used for in the coming sections of the paper is summarized in Table 1. The initial state of the planning is the given system configuration that specifies the number of cells $|C|$. These cells are available for production, by installing the different modules during the reconfiguration. The assembly processes are executed by $j \in J$ different module types, and the total number of modules (resource pool) is n_j. Production planning is solved on a discrete time-horizon T, which consists of periods t with equal length t^{p}. The set of products P includes different products p, which are distinguished by

Table 1. Nomenclature

	Sets
T	set of time periods
P	set of products
J	set of modules
C	set of working cells
	Variables
x_{ptc}	volume of product p produced in period t in cell c
y_{ptc}	indicator: if cell c is producing p in period t
z_{ptc}	setup performed in cell c for product p in period t
s_{pt}	amount of product p delivered in period t
i_{pt}	inventory level of product p in period t
b_{pt}	planned backlogs from product p in period t
h_{ct}	headcount of operators at cell c in period t
	Parameters
t_p^{m}	machine cycle time of product p
t_p^{o}	manual cycle time of product p
t^{r}	duration of a reconfiguration for product p
t^{p}	length of a time period
d_{pt}	volume of product p to be delivered in period t
a_{pc}	indicator: if product p can be assembled in cell c
n_j	amount of modules from type j
r_{jp}	number of modules j required by product p
c^{b}	cost of backlog per product and period
c^{i}	cost of inventory holding per product per period
c^{h}	cost of an operator per period

the following technological parameters. Each product has a total machine cycle time t_p^{m}, which equals to the time that a single product is spent within the assembly cell to be completed. It is important to note that one-piece-flow production is realized in the cells, which means that only one product can be assembled in the cell at a certain point of time. Meanwhile, human operators are performing the preparation of the parts to be loaded in the cell, and removing the finished parts from the output buffer. In most of the cases, the total manual cycle time t_p^{o} and machine cycle time t_p^{m} of a product have the same order of magnitude ($t_p^{\mathrm{o}} \sim t_p^{\mathrm{m}}$), which is important when balancing human and machine capacities in the planning model.

Currently, product-independent reconfiguration time is considered with a length of t^{r}. Each product p has technological requirements that are defined by the amount of modules r_{jp} required from type j to assemble the product. Due to the one-piece-flow production, neither the individual processing times on the modules, nor the routing within the cell are relevant. Although the modules and the cell interfaces are standard ones, there are some technological constraints that must be considered when planning the production, e.g. some modules are not capable of producing a certain product type due to size/workspace limits, or the cell has not enough slots (interfaces) to receive all modules that are necessary to assemble a product type. These constraints are summarized in a compatibility matrix a_{pc}, whose element equals to 1 if product p can be assembled in cell c, and 0 otherwise.

In the analyzed problem, contractual delivery dates are considered, which means that a certain amount d_{pt} from product p should be delivered to the customer in time t. As in a classical lot-sizing problem, main decision is to determine the production lots x_{ptc}, which specify the volume of product p assembled in cell c in period t. Assembled products can be either delivered to the customer (s_{pt}) or kept in the inventory (i_{pt}), however, the latter is associated with certain costs. Besides the assignment of production lots and machine capacities, an important decision is to determine the headcount of operators h_{ct} working at cell c in period t. The objective of production planning is to minimize the overall costs of production and holding while satisfying the customer requirements.

2.4. Emulation of cell control

The simulation model of the reconfigurable cells enables the detailed dynamic performance analysis by executing a production plan. The greatest benefit of using simulation in such cases is the fact that it works without having the real production system. Approaching the execution level of the production planning hierarchy, the evaluation of different production and cell control methods emerges, as the real operation cannot be done without having the detailed control of the system. Therefore, the simulation model has twofold objectives:

- It is responsible for evaluating the quality of the production plan, by calculating the logistics performance indicators like backlogs and inventory levels and considering a dynamic environment.
- It can be used for evaluating different control modes, by connecting the simulation to real controller of the cell. Hence, very detailed analysis can be done by applying the discrete-event controller for virtual commissioning purposes.

In the latter case, the simulation model needs to communicate directly with the cell controller, and process the commands coming from the controller, instead of executing a simulation run in a default way. By this way, not the system but the controller will be evaluated by the model, moreover, different control scenarios can be executed without releasing them to the real production. The necessity of this analysis relies on the fact that reconfigurable hardware (cells) ask for reconfigurable controller, which can be rather complicated based on the scenarios that should be implemented. In order to develop a reliable cell control while keeping the risks and the time consumption of the commissioning procedure on the lowest possible levels, a direct link between the controller and the simulation model needs to be implemented.

3. Workflow of the proposed solution

As introduced in Section 2, two sub-problems emerge when analyzing the problem in question. In order to solve them efficiently, a simulation-based methodology is proposed, which is composed of different modules (Fig. 1). The core element of the methodology is the discrete-event simulation model of the system that is primarily aimed at performing the evaluation of the system configuration, considering a real-world environment. The simulation can be run either in a planning or control mode that can be selected by the user. In planning mode, it takes the calculated production plan as input, and executes it in a dynamic environment. In control mode, it works as an emulator, and executes the commands coming real time from an external cell-controller. Depending on the selected simulation mode, the results of the analysis are detailed data about the logistics KPI realized when executing a production plan, or detailed, control-related performance data.

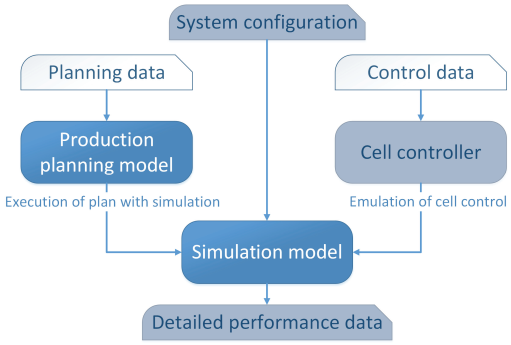

Fig. 1. Scheme of the proposed, simulation-based production planning and control worflow.

3.1. Two-level simulation model

As stated in Section 2.2, the evaluation needs to focus on multiple reconfigurable cells that share the resources, instead of analyzing a single cell only. Besides the general dynamics of production processes, material handling, assembly processes, in- and outbound logistics, reconfiguration of the cells introduce new challenges in the analysis. In order to tackle them, a novel simulation model architecture is proposed, defined specifically for modular reconfigurable systems. Similarly to the assembly cells that are composed of static cell elements and changeable modules, the simulation model has also two main parts: a static configuration controller and the continuously changing detailed cell models (Fig. 2). The core element of the model is the cell controller, which is responsible for representing all processes and objects of the production system except the changeable modules. Static parts of the model are the inbound logistics objects with the buffers, transportation system (if exist) as well as the objects that are responsible for managing the shift calendar of the operators and process the production plan that determine the lot sizes and release times. Besides, the configuration controller manages the inventories by controlling the deliveries and calculating the backlogs.

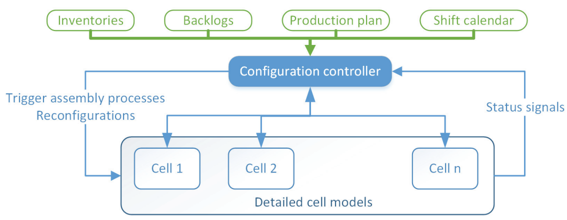

Fig. 2. Scheme of the simulation model defined specifically for modular reconfigurable assembly cells.

Besides the static part of the model, dynamically changing detailed cell models are performing the in-depth simulation of the assembly processes. These models are built-up automatically when reconfiguration takes place. Reconfiguration events are triggered by the configuration controller, when the assembly of the previous lot is finished and a new one is to be started. During a reconfiguration, the necessary modules are installed on the cell by moving them to the proper position in the model and adjusting the proper processing times. The prerequisite of a reconfiguration is that each of the necessary modules need to be available (they can be used by other cells), otherwise the reconfiguration is delayed until each module becomes free. In the detailed cell models, the intra-cell material flow is represented in-detail with the processing and the routing of the parts. The connection among the configuration controller and the cell models is solved by applying event triggers in both direction: the parts are product according to the production plan managed by the controller. If a new part is produced, a trigger event is sent to the detailed cell model that execute the detailed simulation of the assembly processes. After the part is completed, a confirmation signal is sent back to the controller to convey the part in the warehouse or to other processes.

Applying the above described simulation model,the stochasticity of the selected parameters and random events (e.g. module breakdowns) can be set either on the system and cell level, and various analysis can be executed with different levels of detail, while keeping complexity level of the model low.

3.2. Production planning model

Important input of the simulation is the production plan, which is calculated by the planning module of the workflow. The production planning problem is formulated by a mixed integer linear programming model as it follows.

$$\text{minimize} \sum_{p\in P}\sum_{t\in T}\left(c^{\mathrm{b}}b_{pt} + c^{\mathrm{i}}i_{pt}\right) + \sum_{c\in C}\sum_{t\in T}c^{\mathrm{h}}h_{ct} \quad (1)$$

$$\sum_{c\in C}\sum_{p\in T} r_{jp}y_{ptc} \le n_j \qquad \forall\, t, j \quad (2)$$

$$\sum_{p\in P}\left(t^{\mathrm{o}}_{p}x_{ptc} + t^{\mathrm{r}}z_{ptc}\right) \le t^{\mathrm{p}}h_{ct} \qquad \forall\, c, t \quad (3)$$

$$\sum_{p\in P}\left(t^{\mathrm{m}}_{p}x_{ptc} + t^{\mathrm{r}}z_{ptc}\right) \le t^{\mathrm{p}} \qquad \forall\, c, t \quad (4)$$

$$s_{pt} \ge d_{pt} \qquad \forall\, p, t \quad (5)$$

$$\sum_{p\in P} y_{ptc} \le 1 \qquad \forall\, c, t \quad (6)$$

$$x_{ptc} \le \Lambda y_{ptc} \qquad \forall\, c, t, p \quad (7)$$

$$x_{ptc} \ge y_{ptc} \qquad \forall\, c, t, p \quad (8)$$

$$y_{ptc} \le a_{pc} \qquad \forall\, c, t, p \quad (9)$$

$$z_{ptc} \le y_{ptc} \qquad \forall\, c, t, p \quad (10)$$

$$z_{ptc} \ge y_{ptc} - y_{p,t-1,c} \qquad \forall\, c, t, p \quad (11)$$

$$z_{ptc} + \sum_{\substack{q\in P\\ q\ne p}}\left(y_{qtc} - z_{qtc}\right) \le 1 - y_{p,t-1,c} \qquad \forall\, c, t, p \quad (12)$$

$$i_{pt} - b_{pt} = i_{p,t-1,c} - b_{p,t-1,c} - s_{pt} + \sum_{c\in C} x_{ptc} \qquad \forall\, p, t \quad (13)$$

$$z_{ptc}, y_{ptc} \in \{0,1\} \qquad x_{ptc}, s_{pt}, i_{pt}, b_{pt} \in \mathbb{Z}^{+} \quad (14)$$

The objective function of the production planning is the sum of backlog, inventory holding and operator costs that should be minimized (1). The first constraint represents the module requirements of the product, in order to avoid the insufficient amount of resources as they are shared among the cells by the reconfigurations (2). Constraints (3) and (4) respectively state that the manual and machine capacities cannot be exceeded. In case $t^o_p > t^m_p$ (e.g. if several parts need to be handled by the operators), the production takt of the cell is limited by the human capacities, therefore, it is important to allocate enough workforce to maintain the smoothness of production. In case $t^o_p < t^m_p$, the production takt of the cell equals to the machine cycle time, hence, a single operator is enough to perform the manual processes. Inequality (5) states that the customer requested volumes need to be delivered. In case there are not enough products in the inventory, backlogs will occur. Constraints (6-11) represent the reconfiguration requirements when a new product is to be produced in a given cell. Important assumption is that a certain cell c can be reconfigured to a single product p only in a period t. In (7), the coefficient Λ is required to properly calculate the reconfigurations, its lower bound is $\Lambda > t^p/(\max_{p\in P} t^m_p)$. The balance equation (13) is responsible for linking the subsequent time periods with each other through the delivery, inventory and production volumes.

3.3. Simulation-based emulation of cell control

Besides the evaluation of the configuration and execution of the production plan, the simulation model is responsible for evaluating and testing the cell control. In this case, an additional layer between the input sources and the configuration controller is added to completely take the control over the simulation (Fig. 3).

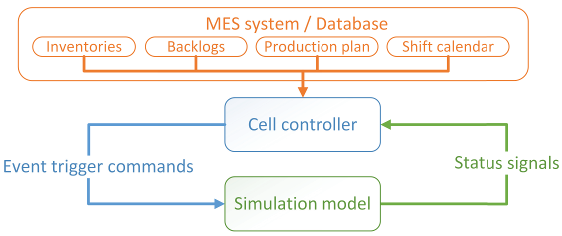

Fig. 3. Emulation of the cell control with the simulation model.

By this way, the simulation model works as an emulator without a predefined simulation logic [8,9]. This logic is replaced by a bidirectional information flow between the model and the cell controller: commands of the cell controller trigger events in the simulation model, which sends back confirmation messages after the execution of the events. The only logic that is implemented in the model are the random disturbances and stochastic parameters that simulate realistic processes. The advantage of this approach is the option of testing the cell control simulating real situations and boosting the commissioning procedure.

4. Experimental results

The efficiency of the proposed solution was tested on a dataset provided by an automotive supplier producing car body parts. In the use case, the assembly of $|P| = 17$ products in $|C| = 5$ reconfigurable cells need to be planned and simulated. The assembly processes can be done by using $|J| = 7$ different module types, each of which is capable of performing a single type of operation. The most important parameters of the products are summarized in Table 2.

Table 2. Product characteristics.

p	t^m_p	t^o_p	r_{1p}	r_{2p}	r_{3p}	r_{4p}	r_{5p}	r_{6p}	r_{7p}
P1	5.9	6.5	2	0	0	0	0	2	0
P2	4	5.4	1	0	2	0	0	1	0
P3	4	4.1	0	1	1	1	0	2	2
P4	4.5	4.9	0	2	2	2	0	0	1
P5	4.8	4.6	1	0	0	2	1	0	0
P6	4.2	4.7	1	0	0	1	2	1	0
P7	6	5.7	0	2	2	0	0	0	2
P8	4.7	6.6	2	0	1	0	0	0	0
P9	5.1	4.1	1	0	0	2	0	1	1
P10	5.9	6.9	2	1	0	0	2	0	0
P11	4.2	4.7	0	1	0	2	1	1	2
P12	5.9	6.5	1	2	2	0	2	0	0
P13	4.5	6.5	0	1	0	2	0	0	1
P14	6	5.3	2	2	2	0	0	0	2
P15	5.1	6.4	0	0	2	0	0	1	2
P16	4.1	7	0	0	1	0	0	2	0
P17	4	5.6	0	1	0	1	0	0	0

First, the simulation model of the system is built in *Siemens Plant Simulation* by using its integrated programming environment to implement the dynamic reconfiguration processes with the configuration controller and the detailed cell models. Besides, the communication layer integrated in the model that enables the user to switch between the emulation and simulation modes. The cell controller itself is designed and implemented by a machine tool builder company in *Java* environment using an actor model. The communication between the controller and the simulation model can be established via TCP/IP protocol, which is capable of sending and receiving messages. For the cell control, a predefined set of commands and messages can be used that can trigger each possible events in the model, and able to report each relevant states of the system.

In the production planning task, several various, realistic scenarios were analyzed to evaluate the model and system performances. In the production planning, a given resource pool was considered without the option of investing in new modules. In order to analyze the resource sharing among the cells, a the following module pool was applied in the planning: $n_j = (6, 5, 6, 5, 7, 6, 5), j \in J$. The production planning was solved on a daily basis, which means that $t^p = 1440$ minutes, and the planning horizon was set to $|T| = 12$ days. Important parameter is the reconfiguration time, which takes $t^r = 100$ minutes, and cca. 20% of the compatibility matrix is a 0 value, which further limits the assignment of products to the cells. The planning model was implemented in *FICO®Xpress* and solved by its default branch and bound method[1], with the criterion that the optimality gap should be at most 8%. The average running time of the production planning problem (it depends mostly on the amount of products to be delivered) was cca. 140 seconds.

In order to evaluate the quality of the calculated plans, each of them were executed by the simulation model of the system. The most important measures of the production planning task are the amount of backlogs and the inventory levels that are realized during the production. The execution of the plans with simulation enables to analyze performance indicators, supposing a realistic environment with stochastic parameters. As machine processing times can be considered to be constant, manual processing times are introduced in the model as a stochastic parameter with normal distribution. With this assumption, a selected production plan was executed several times, applying different mean (μ) and standard deviation (σ) values, which are given in the percentage of the deterministic manual cycle time t_p^o. The input parameters of the experiments and the results are summarized in Table 3, where Δ value is the percental increase of the objective function comparing the result of the optimization and the execution of the plan in a simulation environment. According to the results, the calculated production plans expected to work well in a real production environment, as they keep their feasibility even though the some stochasticity is introduced in the processes. The changes affect only the value of the backlogs, however, the significant increase in costs only incur in case of large changes in the mean values (> 8%). Besides, the results plan is less sensitive for the deviation of the manual cycle times.

Table 3. Experimental results of production planning: *OC* - total operator costs, *BC* - total backlog costs, *IC* - total inventory costs.

Exp.	μ [%]	σ [%]	*OC*	*BC*	*IC*	Δ [%]
01	100	0	40	0	498	0
02	100	6	40	0	498	0
03	100	12	40	0	498	0
04	100	18	40	0	498	0
05	108	0	40	0	498	0
06	108	6	40	300	498	5.6
07	108	12	40	700	498	13.0
08	108	18	40	1200	498	22.3
09	116	0	40	5000	498	92.9
10	116	6	40	3100	498	57.6
11	116	12	40	3000	498	55.8
12	116	18	40	6100	498	113.4

5. Conclusions

In the paper, simulation-based method was introduced to support the design and planning of modular reconfigurable assembly cells. The simulation model is built according to a novel, two-level approach with the static configuration controller and the detailed models of the assembly cells. By this way, the model can be used for two main purposes, taking the given system configuration as an input. On the on hand, the model is capable of evaluating different production plans by introducing stochastic parameters in the execution of the plans. On the other hand, the direct link with the cell controller, and, therefore, the emulation of the cell control can be analyzed. Besides the simulation, a production planning method was also introduced solving a lot-sizing problem with shared resources and reconfigurations. According to the test results, the proposed approach efficiently supports the management of modular reconfigurable cells, and is able to decrease the commissioning time of new cells.

[1] All the computational experiments presented in the paper were performed on a laptop with 8GB RAM, and Intel® Core i5 CPU of 2.6 GHz, and under Windows 8.1 64 bit operating system.

Acknowledgement

Research has been partially supported by the European Union 7th Framework Programme Project No: NMP 2013-609087, Shock-robust Design of Plants and their Supply Chain Networks (RobustPlaNet) and by the Hungarian Scientific Research Fund (OTKA), Grant No. 113038.

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