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Procedia CIRP 3 (2012) 579 – 584

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45th CIRP Conference on Manufacturing Systems 2012

Matching Demand and System Structure in Reconfigurable Assembly Systems

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Abstract

In the paper, a simulation-based technique is focused on that defines the boundaries and components of a reconfigurable assembly system according to historical order-streams. Fluctuating production volumes and "end-of-life-cycle" products require frequent revisions of the production structure applied, in order to gain production space and to level between capacity and throughput of the system. The proposed method separates the low- and high volume products and product families dynamically, by assigning to them the appropriate reconfigurable or dedicated production lines, respectively. A comprehensive industrial case-study and a new indicator on system's operational behavior are presented as well.

Keywords: Reconfigurable assembly system; Self-building simulation

1. Introduction

In several manufacturing systems which handle a larger product portfolio, fluctuating production volumes and "end-of-life-cycle" products require frequent revision of the production structure applied, in order to gain shop-floor space and to level between capacity and throughput of the system. An effective solution to handle the fluctuation in the order-stream is the application of reconfigurable systems (RMS), since they respond to changes by offering focused flexibility on demand by physically reconfiguring the structure of the system [1]. Hence, most reconfigurable systems operate at high level of automation, but there are some industrial processes which require manual assembly system because of the complexity of the assembly tasks, or the high costs of the automated system's implementation.

Digital enterprise technologies, as for example discrete-event simulation (DES), are effective tools both in production-related decision-making processes and in controlling manufacturing systems [2]. For constructing valid models of these systems and their processes, the models should represent the evolution of discrete events in the system, as well as features of the underlying processes [3]. The greatest overall benefit of using simulation in a manufacturing environment is that it can provide a system-wide view of the effect of local changes to the manufacturing system [4].

In the paper, such a simulation-based technique is focused on that defines the boundaries and components of a reconfigurable assembly system according to historical order-streams. The proposed method separates the low- and high volume product families dynamically and by assigning to them the appropriate reconfigurable or dedicated production lines, respectively. Section 3 presents an industrial project that was aimed at implementing a modular manual assembly system.

Because of the numerous and complex design aspects of the proposed system (e.g., space required, human resources, throughput, scheduling efficiency) a DES approach was taken. Section 4 presents how to dynamically evaluate those structural properties that affect directly the system's reconfigurability. In order to support the evaluation of the simulation results, a new production

doi:10.1016/j.procir.2012.07.099

indicator is elaborated. The measures, introduced in Section 5, characterize the reconfigurability of the system designs and help forecast the behavior of the system applying a given production schedule policy to a wide product portfolio.

2. Reconfigurable manufacturing systems

2.1. Challenges of RMS'

The objective of reconfigurable manufacturing system is to provide the functionality and capacity that is needed, and exactly when it is needed [5]. RMS is designed at the outset with a capability for rapid change in structure including both hardware and software components. This way, production capability and even functionality can be adapted in response to changes in market or regulatory requirements [6].

Specifically, the shorter lifetime of products induces a more fluctuating volume and a growing size of product portfolio as well. Therefore, efficient assembly technology is absolutely critical. The industry uses a variety of concepts to meet these requirements. Figure 1 illustrates the areas of utilization for the three most important assembly systems: manual assembly, hybrid assembly and automated assembly.

Choosing the most appropriate assembly concept is a hard decision, since there are several requirements that have to be taken into consideration. From the product point of view, the dimensions, geometry, number of parts and the number of variants are the most important factors. In contrast, management expects high throughput and just-in-time production at a reasonable cost.

However, defining an optimal capacity configuration regarding reconfigurable or dedicated systems on a rolling time horizon is a difficult task. A new model and a numerical study is presented in [7], focusing on the investment point of view. Similarly to RMS, the concept of reconfigurable assembly system (RAS) can be defined, which design is able to meet the previous requirements.

2.2. Proposed RAS design method

In this section, a design method is introduced which defines the boundaries and the components of a reconfigurable assembly system. Concluding from the previous review on reconfigurable manufacturing systems, two main issues are identified when designing production system capacity and considering RAS as an option.

1. Definition of an appropriate product mix for a given time horizon, which could be produced in the reconfigurable assembly system at a balanced utilization level and throughput. Note that usually these measures are also transformed to cost measures.

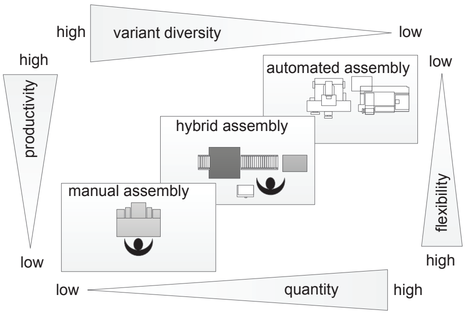

Fig. 1. Utilization areas for manual, hybrid and automated assembly concepts [1]

2. Definition of the equipment requirements, the configuration, and the operational conditions of the proposed reconfigurable assembly system.

At first, the main assumptions and constraints about the whole manufacturing system have to be clearly described. It is assumed that there are production lines (assembly lines), each consisting of workstations. We assume that the number of the workstations is limited, but the number of the applied fixtures is unlimited. At each workstation one or more processes can be executed and the workstations are operated by human operators. Any process can be started only if an operator with the specified skill is available. The assembly lines meet the requirements of a flow-shop system and the production orders are known in advance for the given period. Lines can be dismantled and re-assembled, thus workstations are not necessarily stored in the resource pool.

Regarding the product mix, the decision could be based on the combination of the production volume or revenue and the technology requirements of the production following the steps given as follows. First, define a set including all possible products (or product families). Next calculate the resource demand for each element of this set, by multiplying the sum of production orders by the total work content (including the setups and assembly time of the lines) for the given element. The set of products included into the RAS is filled by starting with the product having the smallest intensity resulted. Next step is to feed the given order-stream into the RAS and calculate the operation time of each line assembled in the system for producing a certain product. The current state of the system could be modeled by a tuple of variables. It consists of the number of lines operating, the number of active production orders, and the workstations activated from the resource pool. Hence, to model the constraints arising by the limited number of resources available, the setup of lines and the calculation of production times, e.g., a DES system can be applied. By iteratively removing the product with the highest intensity from the RAS, and repeating the calculation of the operation times will result in a final set of products, which could be produced in a balanced way in the RAS.

The second problem – selecting machines from the resource pool – could be solved by a systematic search for an appropriate configuration of the RAS. At the current state of the capacity calculation, there is no need for defining exact values, but instead, the boundaries and the main characteristics of the system behavior have to be reflected by the analysis. Most important results of the simulation show the effect of the number of operators and the number of workstations available in the resource pool on utilization and throughput.

3. Industrial case-study

3.1. As-is state of the reorganized assembly system

A real production facility in the automotive industry served as the test bench of the prototype simulation system. The reorganization of the company's production requires a new assembly segment for the low-volume products. Most of these lines manufacture the older products whose yearly amount is about 5-10% of the whole product portfolio. There is only a relatively small shop-floor space for this segment; therefore, it is impossible to assemble each product in a dedicated, highly automated system. The importance of assembly operations is characterized well by the fact that they require typically anywhere from 15% to 70% of the total manufacturing time [1], [8].

The project was aimed at reducing the required space of all the low-volume lines and reorganizing their operation by making them reconfigurable. The main requirements are that the lines have to meet customer orders while occupying the smallest area possible. The assembly processes at lines are manual, supported by various pressing- and screwing-machines. The material flow of the lines is linear, and all the assembly tasks of the products are sequential.

The main question in this case is the following: How many workstations (WS) and operators are necessary to perform the production in face of changeable order demands and limited shop floor space?

Before starting the design the most important task is the mapping of the low-volume products and product families. Products family means that similar products (i.e., similarity regarding structure, dimension, function, or assembly process) are currently assembled on the same line. Most of the products are not individual; they have several variants, which also use the same machines and equipment.

3.2. Conceptual system design

During the reorganization process of the low-volume segment, two main questions had to be answered, accordingly to the issues discussed in Section 2.2.

- How to separate effectively the low- and high-volume product families and assign the appropriate assembly system?
- What are the equipment requirements of the proposed reconfigurable assembly segment, so as to perform continuous production in face of changeable order demands and limited shop floor space?

The basic concept of the new system design was the reconfigurability which is supported by modular assembly lines. Within the mapping process of the production lines, the assembly tasks of each product are categorized systematically. Based on this, eight main assembly tasks could be identified, thus, all the products can be manufactured by the various sequences of these processes. These main tasks can be standardized in terms of their equipment and the workspace requirements. Therefore, it was possible to define eight, so-called standard-workstations with all their equipment, and technological requirements. Such typical standard workstation is the screwing station, which has definite dimensions and interfaces (air, voltage etc.), and supports the production of the variety of a products by using adjustable torque-ranges and changeable bits. Other critical issues are the pressing and testing processes, which are also solved by universal machine designs (changeable interfaces, pressure ranges, tools etc.). The technical feasibility of these machines is proved by the fact that the company already uses some universal test machines in the everyday production. The workstations are mobile, with well-supported alu-frame structure and changeable fixtures.

Another critical point is the logistics interface of the assembly lines, since it is impossible to keep up a constant stock close to them. Therefore, the solution selected uses kits, which are easy to handle, even in case of low product volumes.

The simplified operation of the reconfigurable system is the following:

1. First, the assembly lines is built-up by means of the standard workstations (which are required by the actual line), by moving them next to each other.
2. The operator does the necessary setup tasks, e.g., plugs-in the air connectors, and places the necessary fixtures on the workstations.
3. The operator prepares the necessary parts by using the kits.
4. The operator assembles the products in the required volume.
5. After the assembly process is finished, the operator dismantles the lines, by moving back the workstations to the resource pool.

Based on this dynamically changing assembly system, it is possible to produce all the products of the low-volume segment.

4. Evaluation of the system designed

As it was mentioned previously, the simulation analysis has two main goals: the determination of the system's technical requirements (especially the number of the workstations from each type) and the separation of the low- and high-volume products.

4.1. The model of the reconfigurable system

The system is modeled and simulated in Siemens Plant Simulation, which supports self-building simulation by its built-in programming environment (SimTalk), and graphical interface. Self-building simulation means that the simulation model is built up by means of the combination of the production data as well as the knowledge extracted from the production data (e.g. resource and execution model). Plant Simulation combines a component-based approach with strict object-orientation, so new building blocks can inherit properties and methods from other building blocks and can add and redefine properties and behavior [9].

In order to build the simulation model automatically, all the input data are stored in external table files. The data required by the simulation are the structure of the assembly lines (the sequence of the workstations), the process- and setup times, the configuration of the resource pool (the amount of the workstations) and the production schedule (reflecting the customer demands by production orders). The simulation model loads these values and performs the simulation analysis.

Based on the modeling assumptions like below, it is possible to characterize the proposed system design from a modeling point of view, and to define its boundaries exactly. The structural and operational limitations and the elements of the system's theoretical model are the following:

1. The number of simultaneously operating lines in the system is maximized.
2. Each line can be built-up by the standard workstations.
3. Each operator can perform all the assembly tasks.
4. The production is based on "x-piece flow".
5. Every assembly line work with a single operator.
6. The setup time includes the installation time of the line.
7. In case there are not enough available workstations in the resource pool, the installation of the line is delayed.

4.2. The applied simulation scenario

The main goals of the first, so-called preliminary simulation were to test the behavior of the systems' operation, and to determinate of the initial values. The simulation used a historical schedules provided by the company (for a half-year period). The low-volume portfolio had the 48 lowest volume assembly lines. The main examined value of the first test was the number of simultaneously operating lines; by this way it was possible to identify the high-volume lines. Figure 2 shows that the ramp-down section of the graph is very steep, which means that all the lines have finished the production, while the lines with relatively high work content were still operating (approximately 10% of the whole makespan in the given example). By iteratively removing these lines from the reconfigurable assembly segment, it was possible to distinguish between low-, and high-volume products appropriately even for the reconfigurable or the dedicated segment. Furthermore, the preliminary test showed that the relative occupation of the screwing station (WS1) and the pressing stations (WS3) were remarkably higher than the other ones, which was important during the following evaluation.

The second type of tests was a sensitivity analysis which could estimate the equipment requirements of the system. Based on several simulation scenarios, appropriate resource pool configurations could be selected. This test had several kinds of output values, such as the makespan, the number of setups, the idle time and the sum of setup times (note that all these values are valid within the context of a given production schedule).

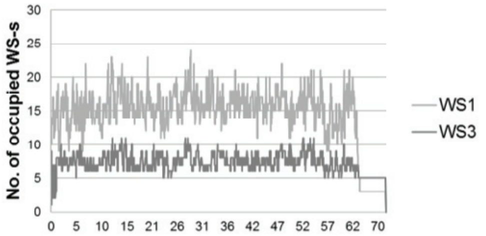

Fig. 2. Occupation of the relevant workstations during the makespan

The second type of tests was a sensitivity analysis which could estimate the equipment requirements of the system. Based on several simulation scenarios, appropriate resource pool configurations could be selected. This test had several kinds of output values, such as the makespan, the number of setups, the idle time and the sum of setup times (note that all these values are valid within the context of a given production schedule).

Table 1. Combination table of the sensitivity analysis' input parameters

	Maximum number of operating lines	Number of WS1	Number of WS3
Value range	6-10	10-19	6-10
Step	1	3	2

The sensitivity analysis used 60 combinations (see Table 1) of three input parameters: the number of available operators, the sets of relevant workstations (WS1 and WS3). Another interesting finding is how the number of a bottleneck workstation (WS1) affects critically the performance of the system.

Accordingly, the increasing number of operators cannot perform shorter makespan and larger throughput, only if the number of the WS1's is increasing (Figure 3). It can be stated that increasing the number of the operators is worth only if a required amount of workstations is available and this action has a positive influence on the makespan (decreases), and on the idle time (stays short) as well. Thus, this analysis gives a lower-bound value of the bottleneck workstations at particular operator availability.

The method introduced in the paper focuses on the technological aspects of the reconfigurable systems. However, regarding investment decisions, the method could be completed with a cost model.

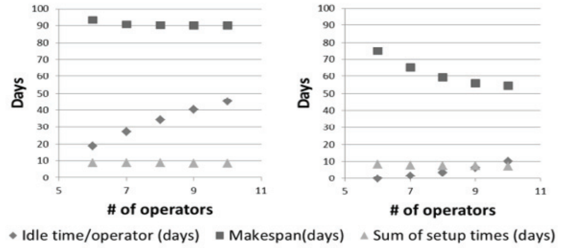

Fig. 3. The effect of the operators' number, in case of 10 WS1 and 16 WS1, respectively

The third type of analysis examined the effect of production scheduling policy to the relevant production indicators. As the product portfolio and the resource pool configuration are already determined, it is possible to examine the effect of the production schedule only. Based on the previously used schedule, it was possible to generate further lists with the same product volumes but different, random-generated orders sequences. By this way, the indicators of the various simulation scenarios became comparable, as they have the same throughput, and only the order of products can affect the results. As it is shown in Figure 4, the schedule order influences highly the system's operation, since the spread of the makespan is about 10% of the average value, which is an extremely high value in case of a reconfigurable system design. Thus, it is very important to select a proper scheduling policy, which can be reviewed easily by the DES simulation.

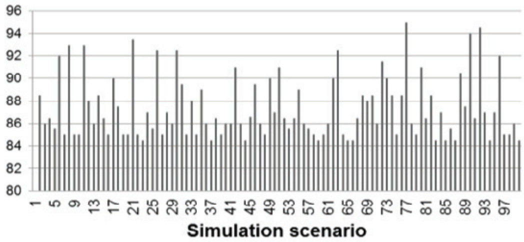

Fig. 4. The results of 100 simulation runs with different schedules

5. Novel indicator for system characterization

Even though discrete event simulation is an effective tool for evaluating the system's operation, there are cases when it is not available or affordable. Similar to flexible manufacturing systems, reconfigurable systems can also be characterized with indicators casted in mathematical formulas. In what follows we propose a novel method for calculating relevant indicator of a reconfigurable system.

Our aim was to estimate the system's performance using various resource pool configurations without performing detailed simulation runs. Hence, we developed a kind of a reconfigurability indicator, which shows the average number of operating lines for a given equipment stock and production schedule. Comparing the calculated value to the simulation results (the maximum number of simultaneously operating lines), the various scenarios can be rated. In ideal case, the difference between the simulation result and the calculated value is minimal, which means that the workstations are well utilized (the idle times are minimal) and the production is continuous. The resultant value is calculated from machine level values; therefore, a proper system configuration can be calculated by iteratively modifying the number of the workstations. The method helps examine the effects of the resource pool configurations to the production indicators (e.g., makespan or idle times).

Consider a reconfigurable assembly system with the boundaries introduced in section 4.1. Using a given schedule and resource pool configuration, the relative work content (W_k) of a particular line is the sum of the line's operation times in the schedule, related to the makespan:

$$W_k = \frac{n_k \cdot p_k + x_k \cdot s_k}{\sum_{k=1}^{K} n_k \cdot p_k \cdot x_k + x_k \cdot s_k} \tag{1}$$

where:

W_k : is the relative work content of line k, which

x_k : is the number occurrence of line k in the schedule

n_k : is the total amount of parts produced on line k

p_k : is the process time/part on line k

s_k : is the setup time of line k

K : is the number of various lines

Since the utilization of various workstation types is changing during the production, it is necessary to know the work content of each machine types:

$$P_i = \sum_{k=1}^{K} m_{ik} \cdot W_k \tag{2}$$

where:

P_i : the work content of workstation type i, and $i=\{1..I\}$

m_{ik} : the required number of workstation type i by line k

Using this value and the resource pool configuration, the average number of simultaneous lines, constrained by the system configuration can be calculated in the following way:

$$L_i = \frac{m_i}{P_i} \tag{3}$$

where m_i : the total number of workstation type i in the system, L_i: the number of simultaneously operating lines, constrained by workstation type i.

Since the number of operating lines is calculated by all types of workstations, it is necessary to take the strictest constraint into consideration.

$$L = \min\{L_1,..,L_I\}\,. \tag{4}$$

In order to evaluate the proposed estimation method, the applied scenarios of the calculations have also been examined by the simulation model. It is remarkable that the correlation between the makespan and the value of 1/L is very strong (Figure 5). Thus, it is possible to estimate the makespan of a given scenario (and resource pool) calculating the value L only.

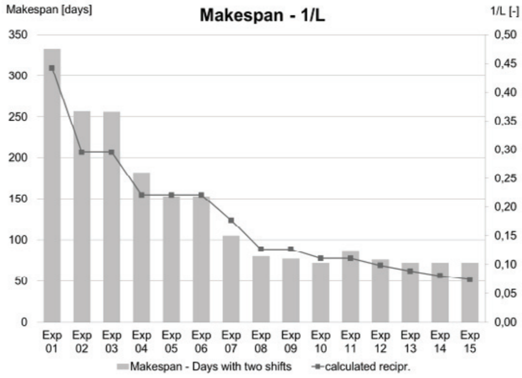

Fig. 5. The comparison of the simulation- and calculation results

6. Summary

A simulation-based technique was introduced in the paper, which defines the boundaries and components of a reconfigurable assembly system according to (historical) order-streams. As it was shown in the literature review, fluctuating production volumes and "end-of-life-cycle" products require frequent revisions of the production structure applied, in order to gain production space and to level between capacity and throughput of the system. However, regarding discrete manufacturing, finding the balanced capacity investment between dedicated and reconfigurable production lines is not a trivial task and requires detailed analysis of the system. Two main topics have been identified as the main issues regarding system design: the definition of such a product mix for a given time horizon that could be produced in the reconfigurable assembly system, and the definition of the equipment requirements, the configuration, as well as the operational conditions of the manufacturing system.

The proposed method separates the low- and high-volume products and product families dynamically, and supports system parameter setting and fine tuning of production capacity.

A real production facility in the automotive industry served as the test bench of the prototype simulation system. The method – based on a self-building modeling technique – matched the order-stream with the resource pool dynamically, effectively supporting the reconfigurable concept. Consequently, the studies showed that considering technological aspects of a production system might support the capacity design decisions. Each configuration of the system could be characterized by the elaborated new indicator reflecting system reconfigurability and performance. The mathematical solutions were evaluated by discrete event simulation.

Further steps are setting up a formal model of the system proposed in section 2.2, which makes it feasible finding optimized solutions for the product mix definition. Elaborating simple, "shop-floor proof" scheduling (sequencing and lot sizing) rules of the production orders, considering optimal line setups is also a future work.

Acknowledgements

Research has been partially supported by National Office for Research and Technology (NKTH) grant "Digital, real-time enterprises and networks", OMFB-01638/2009 grant.

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