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Decision Support System for Joint Product Design and Reconfiguration of Production Systems

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Abstract. Reconfigurable manufacturing systems (RMS) are designed to be able to be reconfigured to produce new items. Nevertheless, reconfigurations of a RMS may be time consuming and costly if they are not considered since early steps of new item design. This work describes a decision support system to automatically generate and test configurations for such RMSs based on a computer-aided design (CAD) model of a new product. The proposed methodology consists of two main steps. First, a matrix of possible assembly plans (taking into account resource/tool compatibility, geometric constraints, ...) is generated with a skill-based comparison between the new item and the production resources. Second, the assembly plan with minimum reconfiguration cost is found through mathematical optimization. The solution is analyzed by a simulation model in the end. Experiments performed on small use case validate the proposed methodology.

Keywords: Decision support system, Reconfigurable manufacturing system, Skill-based approach, Production graph, CAD model, Optimization.

1 Introduction

Reconfigurable manufacturing systems (RMS) [1] allow to manufacture any products of a family within a given set of specifications, due to the possible rearrangement of the tools allocated to each station. Nevertheless, the reconfiguration of a RMS is still time consuming and costly [2], if a newly introduced product is not well designed. Consequently, the RMS reconfiguration costs should be accounted for during the design of the item.

This paper presents a decision support system to automatically generate the assembly plans with minimum reconfiguration cost starting from the computer-aided design (CAD) model of a product. Therefore, product design and production system reconfiguration can be undergone simultaneously [2]. The novelty of the proposed approach allows to jointly make decisions usually made separately by the marketing, engineering

and production department. The joint design of product and manufacturing systems has a significant impact on the cost and time of production [3]. Different approaches exist for the automated assembly plan generation [4, 5, 6]. The design and reconfiguration of production lines are considered in many publications, see for example [7, 8, 9, 10]. A recent state of the art presentation on optimization of RMS is given in [11]. However, to the best of our knowledge, the present paper is the first to simultaneously consider the design of a new product and the line reconfiguration through CAD-models and mathematical optimization.

In this work, we consider a RMS with sequential workstations, a single resource (a robot or a worker) located at a fixed position in each workstation, and a conveyor to transfer the items within the line. Each resource can be equipped with different tools (e.g., griper and screwdriver), and we assume that each task requires a single tool and a single resource for processing. Each tool and resource can execute multiple tasks. In a given configuration of the line, a set of tools is located in each workstation, whereas a set of unavailable tools exists in a tool library. Moving tools between stations or from the tool library to a station results in a reconfiguration cost. More precisely, a reconfiguration cost e_{rt} is associated with the move of a tool t to resource r .

The proposed decision support system is described in section 2. Section 3 presents a case study to validate the proposed approach, and a conclusion completes the paper in section 4.

2 Methodology

Fig. 1 gives an overview of the proposed methodology. First, a production graph is generated from the CAD models of product and production system with a skill-based approach (see Section 2.1). The production graph contains all the data required to reconfigure the line and produce the new item. Second, the solution of an integer linear program (ILP) gives the best tools and tasks affectation. This solution meets the desired takt time and minimizes the reconfiguration cost (see Section 2.2). Finally, a simulation model checks the geometrical and technological feasibility of the solution taking into account for example collision freedom and reachability (see Section 2.3). If the solution is not feasible, the production graph is updated and a new iteration of the mathematical optimization executed.

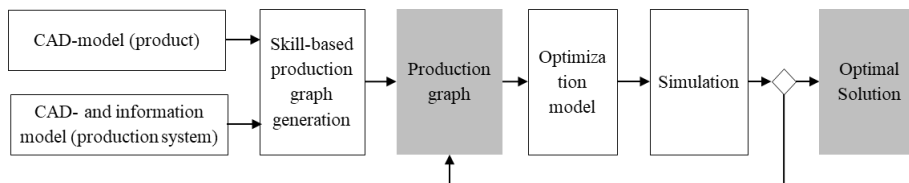


Fig. 1. Schema of proposed approach

2.1 Automatized skill-based generation of production graphs

The proposed approach is described in Fig. 2. For the product analysis step, product requirements are generated through assembly-by-disassembly approach. The assembly-by-disassembly is a multibody simulation where parts of the CAD-model are disassembled collision free. Generated assembly sequences form a precedence graph. In addition, there are CAD-models of the assembly line and its resources. Specific resource parameters are described in a resource library which is built in a structured database. Each resource is described through an information model which describes resource functional skills. In this context, skills (e.g., "moving" or "joining two parts") represent hardware neutral functionalities through semantic modelling [12]. Automatized planning systems often inherit skill-based concepts, since functionalities of abstracted assembly resources are described universally via commands, functions or interfaces [5]. The communication between different production resources and the product to be assembled can be enabled through skills. The assembly of a specific product is defined by demands on production resources to execute individual assembly tasks. Tasks are a set of actions to fulfil specific product requirements such as screwing or joining two parts [13]. Automatized planning systems are therefore enabled by the solution independent representation of product requirements through tasks. Besides technical and economic aspects, the information model takes reconfigurability aspects into account. The outcome of this analysis is a semantic description of the skills of an assembly line.

The requirement skill comparison identifies possible matches between the generated assembly processes and described assembly line skills. The comparison is based on a semantic matching process, that checks if the resource's skills (e.g., join, screw, ...) match the requirements of the task. The resources passing the semantic test are checked through a quantitative parameter analysis, to ensure the parameters (distance of the gripping points, torque of the screw, ...) of the resource match the required parameters of the task (gripping point defined in the CAD model, ...). For each positive match, the tool is added to the set M_{ir} of tools that can execute task i on resource r . The processing time h_{irt} of task t on resource r with tool t is automatically calculated based on position and path information obtained from CAD-models as well as resource information gained from the library. The entire information from product and production system analyses as well as semantic matching process is gathered in the production graph.

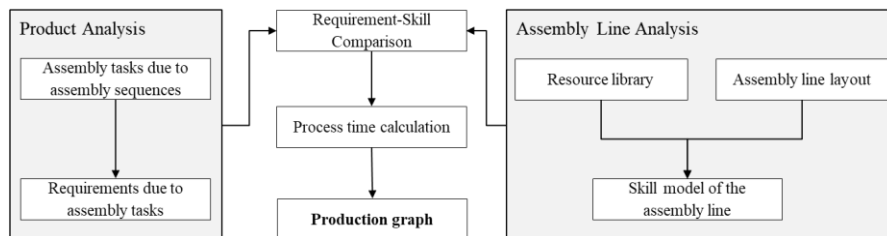


Fig. 2. Flowchart of the production graph generation approach

2.2 Optimization model

The production graph contains the input of the optimization model, namely, the set I_i of immediate predecessors of each task i , the set M_{ir} of tools that can execute task i on resource r , the processing time h_{irt} of task i if executed on resource r with tool t , and the takt time T . Based on this data, the following ILP (Integer Linear Program) is solved to find the assembly plan with minimum reconfiguration cost. The model has two binary decision variables, namely, x_{ir} is equal to 1 if task i is assigned to resource r (0 otherwise), and y_{rt} equals to 1 if tool t is assigned to resource r to process task i (0 otherwise). The proposed ILP is given in equations (1)-(7), where P, N , and R denote the sets of tasks, tools and resources, respectively.

$$\text{Min } z_1 = \sum_{r \in R} \sum_{t \in P} e_{rt} \cdot y_{rt} \quad (1)$$

s.t.

$$\sum_{r \in R} x_{ir} = 1 \quad \forall i \in P \quad (2)$$

$$x_{ir} \leq \sum_{t \in M_{ir}} y_{rt} \quad \forall i \in P, r \in R \quad (3)$$

$$\sum_{r \in R} y_{rt} \leq 1 \quad \forall t \in M_{ir} \quad (4)$$

$$\sum_{t \in M_{ir}} \sum_{i \in K} h_{irt} \cdot x_{ir} \leq T \quad \forall r \in R \quad (5)$$

$$\sum_{r \in R} r \cdot x_{ir} \leq \sum_{r \in R} r \cdot x_{jr} \quad \forall i, j \in P, i \in I_j \quad (6)$$

$$x_{ir}, y_{tr} \in \{0, 1\} \quad \forall r \in R, i \in K, t \in M_{ir} \quad (7)$$

The objective function (1) is to minimize the reconfiguration cost. Constraints (2) state that each task must be processed by exactly one resource. Constraints (3) ensure that a tool is available on the resource to process each assigned task. Constraints (4) prevent to assign a tool to more than one resource. Constraints (5) state that the total processing time on each resource cannot exceed the takt time. Constraints (6) ensure the precedence between the tasks. Constraint (7) gives the domains of the variables.

2.3 Analyzation of feasibility through simulation

A multi-body simulation model is required to analyze the feasibility of the assignment of a tool to a resource to perform a task. Indeed, the skill-based comparison of step 1 does not ensure collision freedom and reachability. However, as the simulations are time consuming, testing all possible triplets (resource, tool, task) is not possible. Consequently, the optimization step is run first, and it might return a solution with assignment (tool, resource, task) leading to collisions. Therefore, the simulation step is run after optimization to check the proposed solution for collision freedom and reachability. The simulation is based on a 3D environment using kinematics (see [6]), and it uses all

available information from the CAD-model and the resource library. In the simulation, collisions between product and resource, resource and surrounding and between different resources are checked to ensure the safety of the process. Further, the simulation analyzes if every position can be reached by the worker or robot to secure feasibility. If the simulation identifies that a tool t cannot be assigned to a resource r to perform a task i , t is removed from the set $M_{r,i}$ in the production graph, and the optimization is repeated. If the simulation gives a positive feedback, the optimal solution is found.

3 Validation of the methodology

Fig. 3 shows a use case where a new product made of five parts (A, B, C, D, E) must be assembled on an existing line. The line has three stations (R1, R2, and W), where R1 and R2 are operated with robots and W is operated by a worker. Three automatic tools T1, T2 and T3 are currently located on R1, but they can as well be moved to R2. Similarly, the line contains three manual tools T4, T5, and T6 located on W (they cannot be used by robots). Finally, the automatic tool T7 can be acquired.

Based on the CAD model, the assembly-by-disassembly approach generates all the necessary processes. In our example, 4 "joining" tasks are created: I1 (Placing B on A), I2 (Placing C on B), I3 (Placing E on B), and I4 (Placing D on B). The assembly-by-disassembly also generates the precedence graph shown in Fig. 3.a.

As shown in Fig. 3.b, the skill model of the current line, the current configuration of the tools in the stations, and the list of the tools existing in the library. Fig. 3.c, describes the type of tasks which can be performed by each pairing of resource and tool. Processing time of each task depending on the pair of tools and resource, and reconfiguration cost of the tools in the line are also shown in Fig. 3.c. The qualitative analysis assigns the resource to the task types, whereas the quantitative analysis checks whether the parameters match (e.g. necessary torque). The production graph contains information about the feasible tasks, reconfigurations (including time and costs), task parameters (e.g. assembly paths, processing times) and precedence graph (e.g. screwing – primary; handling – secondary).

Finally, the ILP (1) - (7) is solved with CPLEX, leading to the optimal solution shown in Fig. 4 with a defined reconfiguration cost. To produce the new item regarding to the obtained production graph, tool T1 must be reassigned from station 1 to station 2. According to the task assignment in the optimal solution tasks I1 and I2 respectively are assigned to the stations 1 and 2. Moreover, two tasks I3 and I4 are executed in station 3 by a worker.

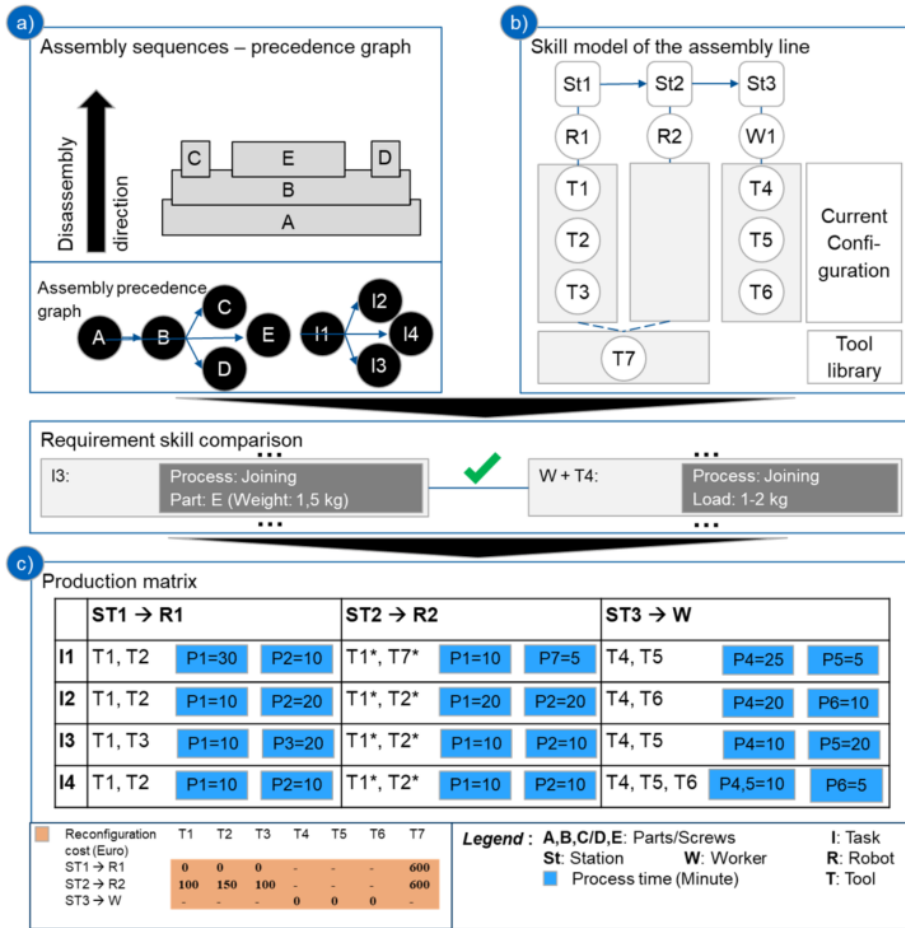


Fig. 3. Generation of the production graph by analysing the CAD model and assembly line

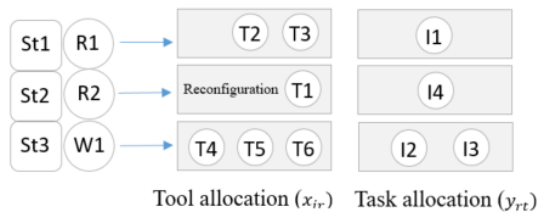


Fig. 4. Optimal solution of use case

4 Conclusion

In this paper, the authors propose a three-step methodology to automatically reconfigure RMS based on the CAD models of new product and existing RMS. First, the set of feasible assembly plans is described using a skill-based comparison of the product and RMS. Then, an ILP is solved to find the new RMS configuration with minimum reconfiguration cost. Finally, a simulation validates the collision freedom and reachability feasibility of the process plan of the new RMS configuration.

While the case study validates the approach, further work is required to implement such a system in practice. First, advanced optimization technics must be designed to handle complex product and large size RMS encountered in practice (with a large number of operations, multiple optimization criterions, ...). Second, to enhance the user experience, an estimation of the reconfiguration costs should be provided in a short amount of time, and suggestions to reduce the reconfiguration cost should be provided to the user. Finally, the generation of constraints directly by the user or by the simulation model should be investigated (similarly to [14]).

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