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Procedia CIRP 57 (2016) 422 – 427

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

Linear Constraint Programming for Cost-Optimized Configuration of Modular Assembly Systems

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Abstract

In this paper, we develop an optimization model for providing a logical layout for reconfigurable assembly systems from a library of available equipment modules. The design problem addresses the challenges in equipment selection to build workstations and subsequently the entire assembly system. All the available equipment modules are assumed to be modular and each of them retains a subset of skills (capabilities). The set of all available equipment modules, their skills, mode of physical connectivity (ports) and costs are known. The objective is to minimize the overall equipment cost without violating their physical connectivity (ports) constraints and the precedence constraints of the assembly process requirements. The analysis of the problem and the state-of-art review steered us to the following: (1) the design problem is very closely related to the assembly line balancing problems; (2) a few Genetic Algorithm (GA) based approaches are already available for the capital cost optimization of multi-part flow-line (MPFL) configurations that includes the operational precedence constraints; (3) to our knowledge, this is the first work to combine the equipment physical connectivity constraints with task precedence in order to provide a valid and optimal configuration solution. A formalized mathematical model is developed to select suitable subsets of equipment modules and group them into workstations to construct an optimal logical layout. A number of scenarios based on an industrial case study are simulated and the results are analysed to evaluate the performance of the proposed models.

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems

Keywords: Configuration; Optimization; Modular Equipment; Assembly Systems

1. Motivation

Manufacturing has a vital role in the global economy and therefore, the concept of Sustainable Manufacturing is becoming more inevitable. Owing to the turbulent market demands, production requirements are becoming highly unpredictable. Customers are constantly demanding highly customized products, which leads to several product variants and increased process complexity. The growing complexity of the product increases the number of variables involved in scheming the best assembly procedures to assemble the products in a manufacturing line. Another major challenge is to reduce the time involved in redesigning the assembly system to accommodate the increasing product variations. To stay competitive, manufacturers must make use of every opportunity to increase their equipment lifespan, throughput, quality and reliability, while managing to reduce costs and respond to changes on an almost daily basis [1].

In addition, several new production paradigms have been developed, such as, Holonic Manufacturing Systems (HMS), Bionic Manufacturing Systems (BMS), Reconfigurable Manufacturing Systems (RMS), Reconfigurable Assembly Systems (RAS), Evolvable Assembly Systems (EPS) and Self-Organizing Assembly Systems (SOAS) [2]. The ability to reconfigure, adapt and respond is realized by grouping the assembly system into sub-systems and modules. In addition to this the SOAS methodology enables a certain degree of autonomy to the system and the modules to control themselves in a decentralized fashion [3].

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems
doi:10.1016/j.procir.2016.11.073

This is a motivation of the ReBORN` Research Project [4], which proposes an autonomous configuration methodology that utilizes all the old, renewed and new equipment modules. The idea is to take advantage of the distributed and decoupled nature of modular assembly system modules and combining it with linear optimization techniques to establish valid and optimal solutions. This paper is mainly focuses on the formal definition of the problem through a linear mathematical model and validating it by an illustrative example.

Nomenclature

A_{PR}	Assembly Process Requirements
S_R	Skill Requirements
E	Equipment Module
E_t	Equipment Module Type
S	Equipment Module's Skill (Capability)
S_t	Skill Type
P	Port
P_t	Port Type
P_{tm}	Male Port (Type Specific)
P_{tf}	Female Port (Type Specific)
P_I	Physical Interface
W	Workstation
C_W	Cost of the Workstation
C_E	Cost of the Equipment Module
e	End of
s	Start of
Z	Time Variable

2. Literature Review

Assembly system configuration that realizes the best possible combination of equipment modules to reduce the production cost is considered to be one of the significant methods of achieving mass customization [1]. Configuration is considered to be a special case of design activity that involves the selection of equipment modules from a predefined repository/ library. However, the numbers of valid configuration design solutions are usually very large. Therefore, the method for the selection of best available modules to form the optimal system configuration had gained an increasing attention in the field of configuration optimization [5].

At present, there are a lot of research literatures available for the optimization of product configurations from various perspectives. MASs configurations are mainly based on the selective assembly of modular equipment modules. Mease et al. [6], Kannan et al. [7] and Matsuura et al. [8] proposed several statistical methods to obtain the optimal binding strategies. Fang et al. [9] methods were based on the selection of classes with equal probabilities. Kannan et al. [10], Asha et al. [11], Kumar et al. [12] and Babu et al. [13] presented various optimization algorithms to match the compatibility classes based on particle-swarm-optimization, artificial immune systems and artificial intelligence. Raj et al. [14] proposed a genetic algorithm which tries to optimize the components mating within a batch.

In addition to the optimization technique it is also necessary to focus on the definition of equipment modules. The definition of equipment module provides the foundation for assembly system configuration. The definition of equipment module is a result of analyzing the similarities between various system components. MAS consists of several sub-systems and modules that enhance the ability of the system to form various system layouts and configurations [15]. MAS promote the independent nature of the modules and make them to be substitutable and transferring materials and information when linked to one another. Furthermore, there are greater chances for the emergence of new capabilities that are the result of module combinations [15]. These combinations determine the configuration variants for a set of given process requirements. Therefore, it can also be said that the configuration constraints and objectives are derived from the Key Performance Indicators (KPIs) that are mentioned in the process requirements [16]. Once the modules are defined under the perspective of a modular architecture, a finite set of equipment modules can potentially deal with an almost infinite set of process requirements [15].

At this point it is also essential to consider the physical connectivity of the modular assembly system's modules. Ports establish the interface that defines the connection between sub-systems or modules in a system configuration. In other words, an assembly system configuration can be represented as modules or sub-systems that are linked to each other through well-defined ports [17]. It has also been realized that there can be numerous valid assembly system configurations for a given product requirement.

In most of the manufacturing paradigms, a common concept of skill is included and it is encapsulated inside the module definition. A new skill concept was introduced in [18], which was based on the open standard IEC 61499. This concept incorporates a precedence based execution that provides a higher level of agility during system configuration. The assembly process requirements are most often represented as a higher level 'Composite Skill', which can be a complex composite of several lower level skills. Unlike the assembly process requirements, the equipment modules skills are represented in a very granular and lower level called 'Atomic skill'. From a configuration point of view, the assembly process domain is constantly evolving and the process of matching of these skills becomes infinitely complex. The work carried out by [18] proposed a methodology that tries to produce configuration solutions by the allocation skill recipes to bridge the gap between the atomic and composite skills as illustrated in Figure 1.

Similar research work initiated by the European projects such as EUPASS and IDEAS, proposed new methodologies for the configuration of MAS, where the major focus was on the definition of skill, skill recipes, equipment physical connectivity and the use of Agent technologies. The complexity and diversity of assembly systems needs configuration solutions that are more precise to the type of the system used. Nevertheless, definition of a configuration methodology that includes a skill model can enable the logical configuration of assembly systems [19].

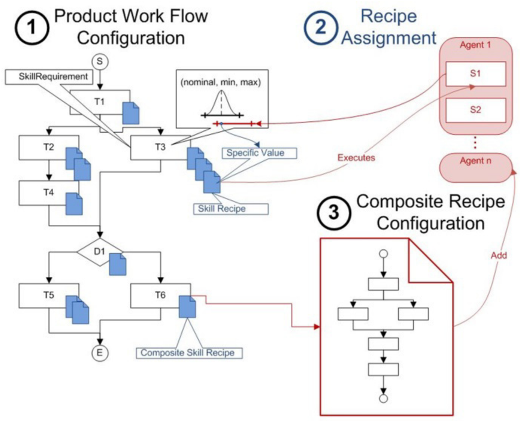

Figure 1: Conceptual Overview of Configuration Process

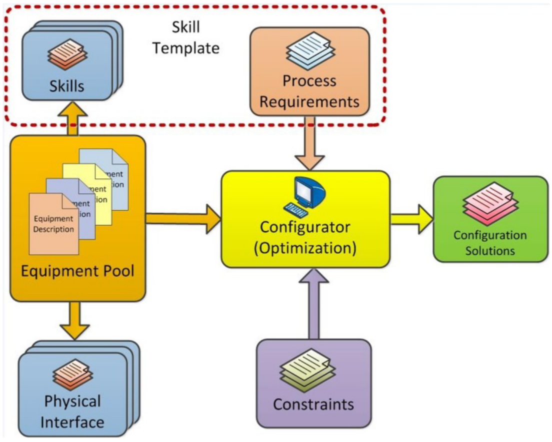

Figure 2: Overview of Problem Definition

Although a lot of research in the field of configuration methods has been carried out, yet the process of MAS configuration is not fully automated. The expected rise in the number of equipment modules will result in the significant increase of the configuration solution space [20]. This highlights the need for a well-defined model for configuration optimization in reasonable time frame. The vision of this paper is to produce optimal configuration solutions combining both physical and logical modularity of the assembly system.

3. Problem Definition

The problem definition for this work was framed from the industrial input gained from the collaborative research project and the current state-of-the-art of the MAS domain. The need for rapid configuration and reconfiguration to enable "Configure to order" of assembly systems has become increasingly important because of the increasing process complexity and the constantly decreasing product life-cycles. Increased modularization of assembly equipment is the fundamental need for cost and time effective configuration methodologies.

At present, the design of assembly systems is mostly human driven based on the expertise of system integrators. This process is often time consuming and cannot guarantee an optimal solution. The concept of MAS is designed in such a way that it enables the functional decoupling of equipment functionalities and standardized interfaces for interchange ability. This has opened the scope for automatic configuration methods. Therefore, it is necessary to formalize these functional capabilities/skills and connectivity constraints, which allows an easy matching between the available capabilities and a set of process requirements.

The MAS configuration problem can be defined as shown in Figure 2. A finite set of process requirements should be translated into assembly system configuration solutions that consist of a finite set of equipment modules. A major issue in dealing with the configuration design problem is to match the process requirement skills with a repository of skills that belongs to the specific equipment modules. This compels to develop a common skill template kind of platform which will be adhered by both equipment skills and requirement skills.

Furthermore, the equipment modules that are capable of fulfilling the process requirement skills should be able to connect with other modules through the means of physical interface. Therefore, it becomes necessary to implement a proper methodology for defining port compatibilities and interface standards.

The solutions optimization significantly depends on the definition of constraints that implements the configuration rules. The choices of available equipment modules that match the process requirement skills can be exhaustive. The optimization algorithm should include an objective function that restricts the selection of equipment modules based on its cost, speed, quality and flexibility. This as a result can subsequently reduce the overall solution space and produce optimal solutions. Another important definition is the formal representation of configuration output. It is necessary to consider the methods that translate the optimization results into configuration outputs. In simple terms the configuration output should represent the bill of equipment modules and the connections between modules.

4. Configuration Optimization Methodology

In order to provide an optimal matching between the process requirements and equipment capabilities (skills) for a particular assembly system, these entities should be defined under the same class model using a common language. The first step in this direction is to define the Assembly Process Requirements (A_{PR}). The A_{PR} can be defined as a finite set of elements that belong to the class Skill Requirement (S_R). Eq.1 illustrates that A_{PR} is a super set and every element of S_{R1} to S_{Rn} is also an element of A_{PR}. This is in principle allows complex composite skills requirements representation, which is out of the scope of this paper. The equipment modules capabilities are represented by the class Skill. Both of these classes encapsulate attributes and one among those is 'Skill Type', which serves as the common terminology for the process of skills matching. This has been mathematically expressed in Eq.2 as, for all ($\forall$) presence of ($\exists$) a skill (S) and skill requirement (S_R), the attribute skill type (S_t) should be contained by these two classes.

$$A_{PR} \supseteq S_{R_1}, S_{R_2}, \ldots\ldots, S_{R_n} \tag{1}$$

$$\forall \exists S \wedge S_R = S \ni S_t \wedge S_R \ni S_t \tag{2}$$

Equipment module (E) is the basic building block of the assembly system and it can be categorized into several types. The equipment module is modeled, as shown in Eq.3, that it should have at least one port (P) and may or may not have any skill (S). For instance, a workbench may not have any skill on its own other than just facilitating the means to mount other components.

$$\forall \exists E = \begin{cases} \exists P \geq 1 \\ \exists S \geq 0 \end{cases} \tag{3}$$

A physical interface can be defined as the combination of two or more ports that can be paired together to establish a connection. Therefore, each physical port belongs to a 'port type' (P_t) that is predefined in the interface library, and each interface should have at least two ports of opposite directions such as, male (P_{tm}) and female (P_{tf}) ports that belongs to the same port type. Therefore, a physical connection between two equipment modules can be established only when they have the same port type and the opposite port directions as illustrated in Eq.4.

$$\forall P_I = \begin{cases} 1, if \begin{cases} E_{t_1} \ni P_{t_{1m}} \\ E_{t_2} \ni P_{t_{1f}} \end{cases} \\ 0, otherwise \end{cases} \tag{4}$$

The choices of available equipment modules that match the process requirement skills can be exhaustive. Therefore, it is necessary to implement some optimization techniques that can reduce the choices of selection based on a few objectives such as cost, quality, time and flexibility. To reduce the complexity of the design problem, this model focuses on designing an assembly system with the least possible cost. Therefore, the objective function that restricts the total cost of building workstations based on the cost of its modules can be expressed as illustrated in Eq.5.

$$Minimize \quad C_{W_i} = \sum_{j=1}^{n} C_{E_{t_j}} \tag{5}$$

The assembly system configuration rules has been translated into four main constraints which defines the boundary of the solution space. In the following, the first constraint is the precedence requirements of the A_{PR}. If Z is considered to be a time variable, then the end (e) and the start (s) of each preceding skill requirement (S_R) can be expressed as illustrated in Eq.6.

$$\forall A_{PR} = \sum_{i=1}^{n} \begin{matrix} [e(S_{R_1}) + Z_1 \leq s(S_{R_2})] + \ldots\ldots + \\ [e(S_{R_{n-1}}) + Z_n \leq s(S_{R_n})] \end{matrix} \tag{6}$$

The second and the most important constraint in dealing with the configuration design problem is mapping all the requirement skills against a repository of skills that belongs to specific equipment modules. For an easier process of skills matching this model represents the skills at their lowest level of granularity. Eq.7 represents that a skill requirement can only be fulfilled if the skill type (S_{tk}) is found to be commonly contained by both skill requirement and the equipment skill.

$$\forall S_R = \begin{cases} 1, if \begin{cases} S_R \ni S_{t_k} \wedge \\ S \ni S_{t_k} \end{cases} \\ 0, otherwise \end{cases} \tag{7}$$

The result of this matching can enumerate a large list of equipment modules that has got the skill type that is similar to those of the requirement skills. The next constraint is to define those equipment modules that are connectable to each other to form workstations and subsequently an assembly cell. The number of equipment modules that a workstation can hold mainly depends on the number of ports (n_{pt}) possessed by modules contained in it. Eq.8-9 illustrates the setup and port compatibilities of a workstation, where a base frame or table holds the other modules contained in it.

$$\forall W = \begin{cases} 1, if \begin{cases} \exists E_{t_1} = 1 \\ \exists E_{t_2} \leq nP_{t_1} \rightarrow (E_{t_1} \ni nP_{t_1}) \\ \ldots. \\ \exists E_{t_n} \leq nP_{t_n} \rightarrow (E_{t_{n-1}} \ni nP_{t_n}) \end{cases} \\ 0, otherwise \end{cases} \tag{8}$$

$$\forall W = \begin{cases} 1, if \begin{cases} E_{t_1} \ni P_{t_{1f}}, P_{t_{2m}} \\ E_{t_2} \ni P_{t_{1m}} \\ E_{t_{n-1}} \ni P_{t_{2m}}, P_{t_{nf}} \\ E_{t_n} \ni P_{t_{nm}} \end{cases} \\ 0, otherwise \end{cases} \tag{9}$$

It is also important to understand that the physical connections in most cases are across different levels, i.e. between workstations or various modules in a workstation. This method and the model for configuration optimization can be extended further to adapt complexities such as the inclusion of composite skills, recipes and other complex constraints and objectives.

5. Illustrative Example

This example illustrates the principles of configuration optimization that includes the assembly task precedence and the physical connectivity that governs the system build. It uses the ReBorn architecture, to implement the industrial test case information provided by PARO AG, an associate partner of ReBorn. This information is a specific representation of an assembly facility that is used for assembling several product variants. PARO AG is a special purpose machine and systems builder, particularly focused on the development of technologies for the automation of assembly systems.

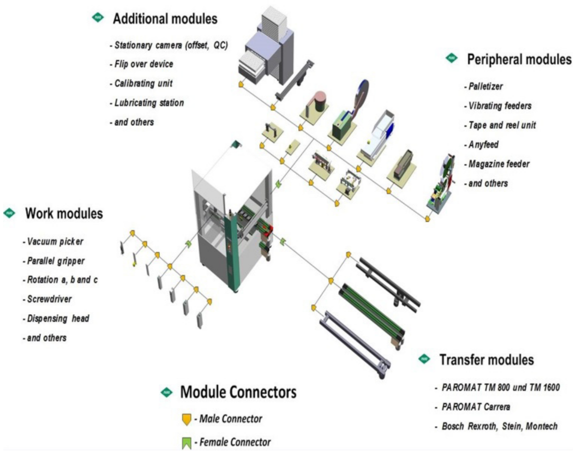

Figure 3: Overview of PARO AG's Workstation

The aim is to demonstrate the strategies and technologies that can support the configuration of an assembly cell, workstations and its sub-assemblies to form a new assembly cell layout for a set of given assembly tasks. The sample assembly scenario presented for this use case includes PARO AG's flexible assembly workstation is shown in Figure 3, which has several optional modules, which can be added or removed depending upon its requirements. The workstation can include four work modules (tools), two additional modules (special handling), four peripheral modules (feeders) and one transfer module (conveyors). These numbers corresponds to the limitation of the number of ports available to connect these modules.

IBM ILOG CPLEX CP Optimizer is one of the advanced optimization programming system, which is designed especially for easy-to-use, model and run optimization models. The example considers a very simple sequence of assembly process requirements to keep the solution space smaller and easier to validate. The skill requirements and PARO AG's equipment modules was declared as the input data and are aligned to the model discussed earlier. The unique Id's of the process requirement skills are used for the representation of the precedence constraints with simple before and after relationship. In a similar way the unique Id's of the equipment modules are used to point their respective skills and ports. The process requirement skills and the equipment module's skills possess a data entity called skill type, which serves as a common terminology for the process of skills matching. Additionally, every equipment module is described with its purchasing cost and type such as work modules, gantry, conveyor and station frame (Figure 4).

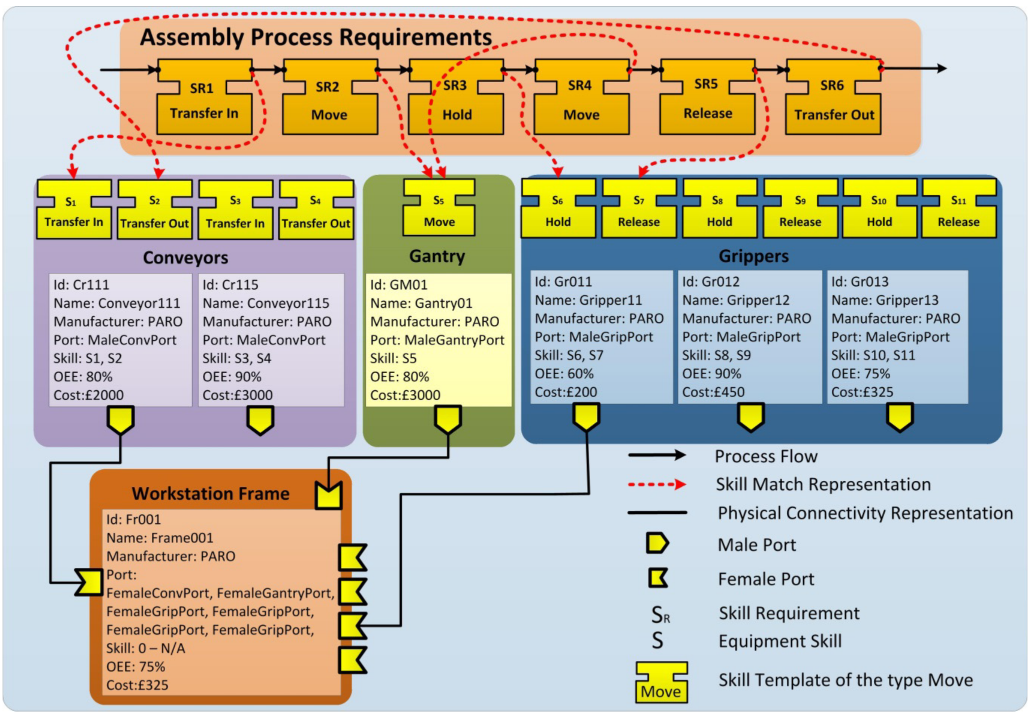

Figure 4: Overview of Configuration Process

An optimization model was developed with an objective to reduce the overall build cost of the system. The decision variables for precedence relations, skills matching, port compatibilities and physical requirements were declared. The four main constraints discussed in the model earlier were also incorporated in the CPLEX optimization model. The model was executed and the resultant skill matching via skill type is also shown in Figure 4.

The selected equipment modules were sorted as workstations which can be connected to each other via their port compatibilities. The decision variable that represents the workstation and the equipment modules contained in it is illustrated in Table 1. Therefore, it means that the sets of workstations possess sets of skills, which can be directly matched to fulfill the process requirement skills. The objective function of the model is defined in such a way that it minimizes the cost of workstation generation. Based on the developed objective function CPLEX identified the workstation01 as the optimal solution for this problem.

Table 1: Workstation configuration and its respective cost

Workstation Vs Modules	Frame	Conveyor	Gantry	Gripper	Cost
Workstation01	Frame001	Cr111	GM01	Gr011	5525
Workstation02	Frame001	Cr111	GM01	Gr012	5775
Workstation03	Frame001	Cr111	GM01	Gr013	5650
Workstation04	Frame001	Cr115	GM01	Gr011	6525
Workstation05	Frame001	Cr115	GM01	Gr012	6775
Workstation06	Frame001	Cr115	GM01	Gr013	6650

6. Conclusion

This paper proposes a formalized linear mathematical model for a cost based configuration optimization of MAS. This model signifies that the assembly task precedence can influence the physical connection and hardware arrangement of the system. The use of assembly task precedencies and port compatibilities in the design problem reduces the search space to finite number equipment module combinations. This paper also reports on the use of CPLEX to implement the methodology. ReBORN, utilizes a wide variety of tools and the integration to implement the described methodology will be demonstrated in the course of the Project.

Further work will focus on the reuse of equipment modules and their optimized use in new manufacturing lines. There is also an immediate possible scope to include more variations to the configuration problem, such as cycle time, quality, life cycle costing and reliability based parameters. The frequent assessment of configuration and reconfiguration of assembly systems that includes reused modules can contribute more towards the concept of Evolvable Production Systems (EPS).

Acknowledgements

The reported work is partially funded by the European Commission as part of the CP-FP 609223 ReBORN project. The support is gratefully acknowledged.

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