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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.

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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].

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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].