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A multi-objective GA-based optimisation for holistic Manufacturing, transportation and Assembly of precast construction

B. Anvari*, P. Angeloudis, W.Y. Ochieng

Centre for Transport Studies, Department of Civil & Environmental Eng., Imperial College London, SW7 2BU, United Kingdom

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ABSTRACT

Resource scheduling of construction proposals allows project managers to assess resource requirements, provide costs and analyse potential delays. The Manufacturing, transportation and Assembly (MtA) sectors of precast construction projects are strongly linked, but considered separately during the scheduling phase. However, it is important to evaluate the cost and time impacts of consequential decisions from manufacturing up to assembly. In this paper, a multi-objective Genetic Algorithm-based (GA-based) searching technique is proposed to solve unified MtA resource scheduling problems (which are equivalent to extended Flexible Job Shop Scheduling Problems). To the best of the authors' knowledge, this is the first time that a GA-based optimisation approach is applied to a holistic MtA problem with the aim of minimising time and cost while maximising safety. The model is evaluated and compared to other exact and non-exact models using instances from the literature and scenarios inspired from real precast constructions.

1. Introduction

Prefabrication has been around for many decades, even centuries in the US and many European countries. However, its concept and construction practices are evolving. The Renaissance architecture and master builder Andrea Palladio standardised and prefabricated columns and stairs because of the growing demand for palaces and villas of the same style [1]. Prefabrication was then used in Europe for replacing houses that were destroyed in World War I. After World War II, there was a need for rapid and low-cost prefabricated housing for military personnel in the US [2]. Thus, there has been a continual need for prefabrication around the world for centuries, but the need is ever changing with the time and new technologies. Design for Manufacturing and Assembly (DfMA) is a simultaneous design and engineering approach where construction components are manufactured and (sub-)assembled in a factory or warehouse, before being delivered to a construction site for installation. DfMA makes use of prefabrication techniques in order to utilise construction schedule, cost, workforce, safety and quality. When optimising prefabrication, it is crucial how a project is divided into smaller parts such as a manufacturing line or an assembly line. By then combining smaller parts, larger elements can be incorporated into the building system. Haas [3] identified the driving factors being cost and schedule for adopting prefabrication in industrial projects as the most critical factors (see Fig. 1a). The results also show that DfMA techniques have a significant positive impact on safety, quality and efficiency at every stage of the project. The time and cost savings due to prefabrication is reported as 66% and 65% in American projects as shown in Fig. 1b and c.

DfMA might not always be a better choice than conventional construction, i.e., transporting structural materials to the building site and assembling on-site [5]. For instance, considerable cost overruns and project management issues have been associated with prefabrication from manufacturing up to assembly. The decision on whether prefabricating components of a building or even an entire building is often based on subjective judgment rather than a thorough analysis of consequential decisions in the MtA sectors [6,7].

Scheduling in a precast construction project is a temporary execution plan of a DfMA proposal. A project schedule reports on the time and order, in which tasks need to take place, and their allocated resources. It reflects required costs and resources to deliver the project; it can provide delay analysis to avoid exceeding the scope of the project or budgetary constraints. The schedule might highlight potential problems before they arise. Resource scheduling is an assignment problem and describes in detail when to accomplish tasks and how to utilise resources assuring the project's objectives. Scheduling requires selecting resource types (such as machineries, cranes, and workforce), determining the required number of each resource, and allocating them to simultaneously executed jobs (e.g., manufacturing a number of different components) over time

* Corresponding author.
E-mail address: b.anvari09@imperial.ac.uk (B. Anvari).

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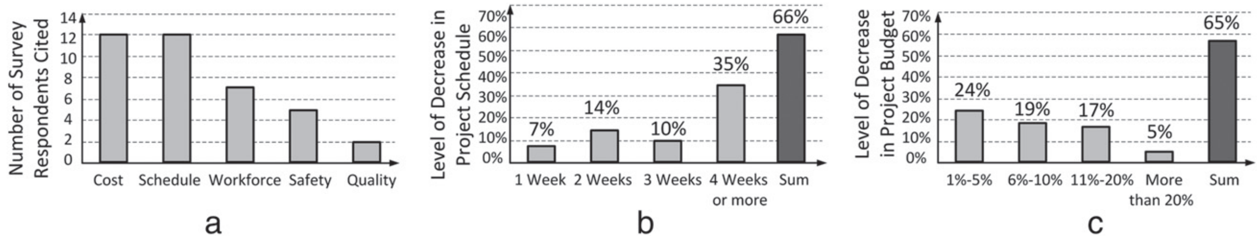

Fig. 1. (a) Comparison between the driving factors for prefabrication [3], (b) level of decrease in project schedule and (c) in project budget due to prefabrication in the US [4].

to maximise productivity subject to the constraints (e.g., limited number of workforce, early start dates, late finish date). A sufficient number and type of resources is crucial for managing demand fluctuation, procurement processes and machine failures. Each sector can process a limited number of tasks at a time; each resource can execute at most one task at a time. Resource scheduling affects and is affected by the manufacturing factory, transportation options and the construction site.

Nowadays, resource scheduling of a DfMA plan is not performed comprehensively: On the one hand, the available decision-making support tools do not cover the combined performance attributes of MtA sectors while evaluating prefabricated construction methods. On the other hand, they do not consider an optimal schedule for the combined MtA sectors before comparing conventional construction plan to prefabricated construction one. It is therefore essential to implement a decision support tool which considers all three MtA sectors as a unified system and acknowledges multiple objectives of the construction project. Hence, this paper proposes a Genetic Algorithm-based (GA-based) technique for solving a unified MtA construction system. The contributions are:

- The prefabrication scheduling problem has been considered as a holistic/unified MtA problem which needs to be solved.
- Due to the complexity of this unified MtA construction scheduling problem (which is equivalent to a complex extended Flexible Job Shop Scheduling Problem), a GA-based optimisation algorithm is applied for the first time. This non-exact model will return a good sub-optimal result in less time than exact methods.
- The presented GA-based technique is multi-objective with one dominant objective function.

To evaluate the quality of the proposed GA for solving flexible job shop problems, the model is compared with other exact and non-exact models using instances from the literature and scenarios inspired by real data from precast construction projects.

Section 2 provides a summary of the available prefabrication decision-making tools and construction scheduling models and identifies the issues of excising algorithms. The detailed description of the problem in the prefabricated construction, input/output decision variables, resource constrains, the optimisation objectives and the framework for resource scheduling a unified MtA system are described in Section 3. This leads to defining the MtA system in terms of a Resource-constrained Extended Flexible Job Shop Scheduling (REFJSS) problem with the aim of minimising the total completion time and cost. These types of problems are NP-complete problems and computationally demanding to solve [8]. Section 4 presents the MILP formulation for the REFJSS and the assumptions. Evolutionary algorithms such as the GA are suitable in finding a solution that is close to the optimal and satisfies the constraints of complex problems. In order to solve the REFJSS problem, a GA-based approach is presented in Section 5, along with a custom tool developed in C# that allows evaluating different prefabrication scenarios. The numerical results of the presented algorithm for different instances from real world scenarios and the literature are presented in Section 6. The general conclusions and future work are summarised in Section 7.

2. Background

Having presented the practical advantages of developing a decision support tool and optimising the schedule for a unified MtA system, Section 2.1 summarises the available decision-making tools for choosing a construction method. In Section 2.2, an overview of the current construction scheduling models is provided.

2.1. Decision-making tools for construction techniques

With regard to construction prefabrication, Murtaza et al. [9] developed the MOdulariz Decision EXpert (MODEX) system to help judging the feasibility and financial benefits of modular prefabrication for a power plant project. MODEX is based on a hybrid expert system, combining an Expert Decision System and a Decision Support System. It follows decision rules set by experts in its feasibility analysis and reports the cost of different degrees of prefabrication in the financial analysis. In the feasibility analysis, MODEX asks a user a series of qualitative questions regarding different factors that influence the prefabrication process. It then computes the total weighted feasibility value, applying preset relative weights, and compares this feasibility score to a pre-set threshold before making a recommendation. In the financial stage of the analysis, MODEX asks for the estimated project cost and schedule, and uses an analytical method to evaluate the cost and time savings associated with different levels of prefabrication. MODEX's recommendation making process is not transparent, however, and it is not clear how the total cost is distributed. In addition, MODEX's decision rules needs to be kept updated as relevant expertise evolves.

Murtaza and Fisher [10] developed a further model, called Neuromodex, for construction method decision-making processes. Neuromodex is based on a neural network system and uses different decision factors relating to a specific project (e.g. location, labour and environmental) as input values, forms a pattern, and then relate this input pattern with one of the output patterns (conventional, semi-prefabrication or prefabrication). In order to recognize the input patterns and produce rational and effective decisions, the neural network needs to be trained based on past modularization decisions. Neuromodex uses MODEX for this training process, with the assumption that past principles using prefabrication were correct.

Song et al. [5] also presented a decision-making framework and a computerized tool to validate the applicability of prefabrication methods in industrial projects. Their decision framework has three levels (strategic level 1, strategic 2 and tactical level). The first two