Decision Support System for Modular Construction Scheduling

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Abstract –

The use of modular construction as opposed to traditional on-site construction presents an opportunity to improve a project's economic and sustainable performance. At the same time, substantial savings in the overall project's duration can be achieved. The potential for reducing the overall make-span period involved in manufacturing and assembling the modularised components, along with the constant need for aligning the work schedule with the in-house manufacturing schedule, leads to the need for a repetitive scheduling optimisation procedure for modular manufacturing operations. This paper presents a framework and a decision support system to schedule operations in modular building factories. The framework is divided into 3 layers; the first layer concerns the assignment of workers to workstations; the second layer solves the scheduling of jobs to workstations while the last layer governs the overall operations of production lines through formulating a parallel machine scheduling problem. For demonstration purposes, a computational test is conducted on the final optimisation stage using a practical case study to solve the parallel machine scheduling problem. To account for resource allocation and levelling, the model is presented as a resource constraint one. Results reveal the satisfactory performance of the proposed model.

Keywords –

Resource-constrained project scheduling; Parallel machine scheduling problem; Modular construction; Optimisation; Mixed Integer Programming

1 Introduction

Managing projects so that they are delivered in the shortest possible time frame is considered one of the main challenges faced by project managers. In a bid to avoid overrunning the project's time duration, many methods can be utilised to better enhance the overall project management procedure. This includes traditional scheduling techniques based on the Critical Path Method (CPM), Program Evaluation Review Technique (PERT) and Monte Carlo simulation [1]. Handling the multi-tasking nature that arises in some projects is however difficult to deal with using such planning methods [2].

A main determinant of a project's production rate, which will influence its completion time, is the construction method adopted. Apart from the traditional on-site construction process, where the whole project is accomplished through building components produced on site, the recent trend in research has focused on an alternative method of construction, namely off-site prefabrication. Classes of off-site construction vary depending on the degree of prefabrication. Modular construction, which has the highest level of prefabrication, involves the pre-fabrication of volumetric building components in a controlled environment, which are then transported to be installed on the construction site [3]. The process of modular construction conforms to the industrial and manufacturing process [4]. As a result, the applications of principles from these industries are well adapted to the construction environment presented in modular building factories [5]. These include make-span and throughput, which strongly impact the scheduling of components within modular factories [6].

Currently, the process of scheduling production lines in modular construction is achieved based on the experience of the factory superintendent [7]. This process however is prone to errors, particularly due to neglecting possible resource limitations for processing work on the floor shop [8]. Additionally, deploying traditional scheduling techniques usually results in solutions that are not consistently in line with progress on the manufacturing floor [9]. Within modular construction, the productivity of a factory is directly influenced by the effectiveness of the scheduling method adopted [10]. As a result, it is important to consider appropriate scheduling techniques that are adapted to the specific environment of modular construction.

A common scheduling technique applied in manufacturing is that relating to parallel machine scheduling. Due to the similarities that exist between conventional manufacturing and modular construction production systems, such methods can be extended to schedule the production line typical of modular construction factories. The parallel machine scheduling problem has been extensively studied in the literature [11]–[13]. In such problems, the objective is to schedule jobs so that the weighted sum of completion times of the jobs is minimised. By varying the processing time of machines several variants of the problem can be examined, including identical, uniform and non-identical machines [12].

This research investigates the scheduling of modular construction elements within a factory production line and presents a decision support system (DSS) comprised of three optimisation layers. A resource-constraint parallel machine scheduling problem is then formulated for the last optimisation stage and presented, assuming input from the initial two stages. A Mixed Integer Programming (MIP) model is proposed for such purpose which integrates the resource limitations and processing capacities of the machines involved in the modular construction.

The organisation of the paper is as follows. In the next section a description of the framework and the DSS is presented. An explanation of one of the layers for which an optimisation problem is to be presented follows. The notation set making up the proposed model is later highlighted along with the associated mathematical model. A practical example is used to demonstrate the model's applicability. Concluding remarks are presented at the end.

2 Decision Support Framework

Fig.1 highlights the typical layout of modular factories. Each component to be built, referred to as a job in this paper, will have to go through a set of workstations, shown as rectangles in Fig. 1. A workstation is defined as a site within the systematic production process where a particular activity is undertaken on a specific job i.e. a building element. Common workstations in modular factories include areas for welding components together, platforms where the structure is framed, and carpentry workshop; the combination of such workstations is what constitutes a production line. A production line is demarcated by the flow of building elements from one workshop to the next. A total of three production lines is thus shown in Fig. 1. The scheduling problem within a modular factory consists of assigning workers to the workstations based on their skill sets, assigning building elements to workstations and scheduling the production line so that the sequence of workstations in each production line is optimised for performance.

In order to optimise the operations within a modular factory setting, a DSS is presented. Fig. 2 highlights the main components making up the system. Three units make up the framework proposed. The first unit, labelled as the Scheduling Unit, incorporates the algorithms necessary for scheduling the operations. These algorithms are grouped into three categories, according to the stage of the optimisation that is performed. This reflects the multi-stage nature of the scheduling problem at hand. At the first stage of the optimisation, the first set of algorithms assign workers to the workstations. The second optimisation stage concerns the scheduling of jobs to workstations, based on resource requirements. At this stage, a buffer between each workstation needs to be considered since the process would not realistically flow continuously, with workstations requiring some preparation time between jobs. For the last stage of the optimisation, the overall production line is optimised by solving a parallel machine scheduling problem. Each production line is referred to as a *machine* in this paper.

The second unit within the DSS of Fig. 2 is a Simulator which gets activated based on a pre-defined set of triggers. These triggers are what can initiate a change to the assignments made in the first two stages of the optimisation (resources and jobs). Major triggers include changes to designs of building elements based on client requests, failure of machines, shortage of workers, increased demand for a product and delays in material deliveries. The main purpose of the simulator is to capture the time frames within the overall production line at which change is induced by the triggers. This enables the identification of the time at which the framework should loop back to re-solve the multi-stage optimisation in the Scheduling Unit. Once the schedules are produced, the simulator is re-activated to keep a record of the time scale.

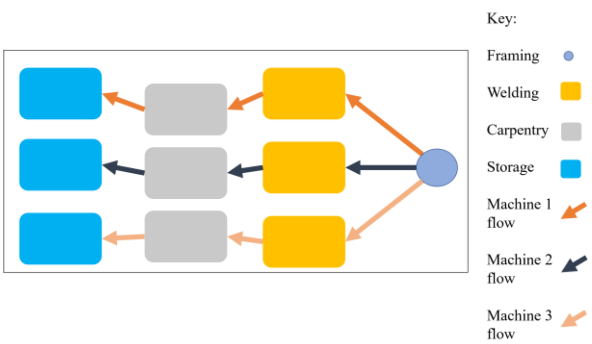

Fig. 1 Simplified plan view of typical modular factory layout. Each machine workflow is comprised of several workstations

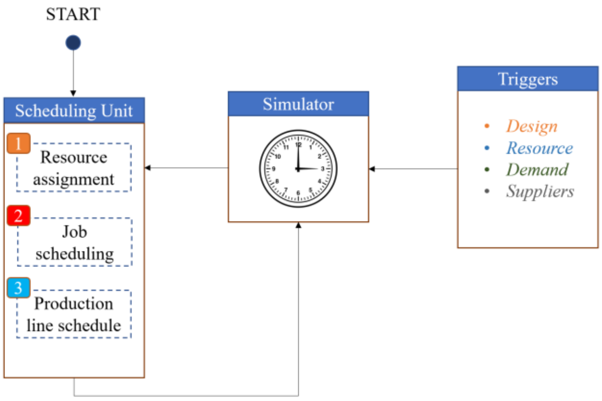

Fig. 2 Decision support system for modular construction scheduling

In the next section, the formulations for the parallel machine scheduling problem solved at the third stage of the optimisation is presented, assuming the assignments from the first two stages have already been determined.

2.1 Parallel Machine Scheduling

Since workstations are grouped together to form machines where each machine is assumed to have the same set of workstations, the problem solved at the third stage of the optimisation can be appropriately modelled as a parallel machine scheduling problem. As shown in Fig. 1, a factory setting can have several machines, with each machine having a configuration that is composed of the same workstation types. The processing time of a job by a machine is a function of the assignment of jobs made; the greater the number of jobs assigned to a machine, the longer the processing time required by the machine. Unlike the traditional parallel machine scheduling problem [12], the problem investigated in this paper allows for a machine to process more than one job at a time

When scheduling the production lines, it is also necessary to apply resource constraints to the problem, to ensure that machines are not overloaded. Given the limited availability of resources, the aim of the scheduling model presented is to appropriately schedule the jobs in a way that minimises the overall production times of the overall machines, while considering reasonable resource capacities. The next section presents the notation for the third optimisation stage.

2.2 Notation

Table 1 outlines the notation set adopted in the proposed model.

Table 1 Notation Description

Symbol	Description
I	Set of machines, indexed by i
J	Set of jobs, indexed by j, k
D_j	Duration assigned to job $j \in J$
L_i	Resource limit assigned to machine $i \in I$
M	Arbitrary large number
x_{ij}	Binary variable, which equals 1 if job j is assigned to machine i, and 0 otherwise
β_{jk}	Auxiliary binary variable
γ_{kj}	Auxiliary binary variable
f_j	Finish time of job j

2.3 Mathematical Model

The proposed model to solve the machine scheduling problem at the third stage of the optimisation is given as follows:

$$\text{minimise } \max_{j\in J}\left\{f_j\right\} \quad (1)$$

subject to

$$\sum_{j\in J} x_{ij} \le L_i \quad \forall i \in I \quad (2)$$

$$\sum_{i\in I} x_{ij} = 1 \quad \forall j \in J \quad (3)$$

$$\alpha_{ijk} \le x_{ij} \quad \forall i \in I, \forall j,k \in J : j > k \quad (4)$$

$$\alpha_{ijk} \le x_{ik} \quad \forall i \in I, \forall j,k \in J : j > k \quad (5)$$

$$\alpha_{ijk} \ge x_{ij} + x_{ik} - 1 \quad \forall i \in I, \forall j,k \in J : j > k \quad (6)$$

$$\left(1-\alpha_{ijk}\right)+\gamma_{ijk}+\beta_{ijk}\geq 1 \quad \forall i\in I,\forall j,k\in J: j>k \tag{7}$$

$$f_k - f_j \geq 0.8D_k\gamma_{ijk} - M\left(1-\gamma_{ijk}\right) \quad \forall i\in I,\forall k,j\in J: j>k \tag{8}$$

$$f_j - f_k \geq 0.8D_j\beta_{ijk} - M\left(1-\beta_{ijk}\right) \quad \forall i\in I,\forall j,k\in J: j>k \tag{9}$$

$$f_j \geq D_j \quad \forall j\in J \tag{10}$$

$$x_{ij}\in\{0,1\} \quad \forall i\in I,\forall j\in J \tag{11}$$

$$\beta_{jk},\gamma_{jk}\in\{0,1\} \quad \forall j,k\in J: j>k \tag{12}$$

$$\alpha_{ijk}\geq 0 \quad \forall i\in I,\forall j,k\in J: j>k \tag{13}$$

$$f_j\in\mathbf{R}^+ \quad \forall j\in J \tag{14}$$

Eq. (1) defines the objective function, which minimises the production make-span. Eq. (2) states that each machine has an associated resource limit in terms of the total number of jobs that can be scheduled to it during a particular production stage. Eq. (3) requires that each job is scheduled. The scheduling constraints, Eq. (4) – Eq. (6) are linearization constraints, while Eq. (7) – (9) represent precedence relationship between scheduled jobs. In particular, for any two jobs that are scheduled to the same machine, a minimum of 20% completion rate of the first job needs to be achieved before another one can be started. This ensures that the resource availability for the workstations making up the individual machines does not impact the productivity of the respective machine. The 20 % figure is obtained after consulting with industry practitioners and can be adjusted to suit the case being considered. Eq. (10) requires that the finish time of a job to at least equal its duration. The domain of the binary variables is given by Eq. (11) – Eq. (12), while the domain of the continuous variable is defined in Eq. (13) - Eq. (14).

3 Case Study

To maintain the brevity of the discussion presented in this paper and to prove the concepts proposed, the DSS is presented through applications of a single iteration of the model on a practical example. The case study is representative of the production line of a typical modular construction factory; its layout plan is shown in Fig. 3.

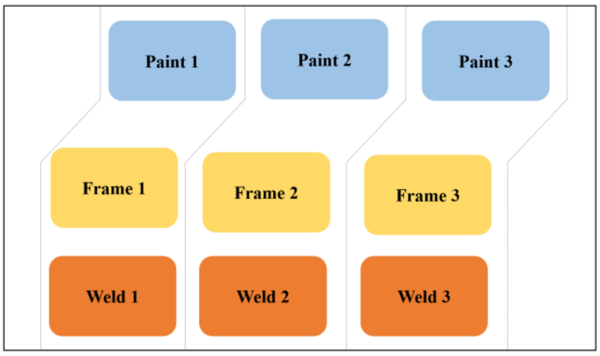

Fig. 3 Plan view of the case study

The project of the case study is comprised of 7 jobs in total, each with a specified duration, as shown in Table 2. Jobs are assumed to be independent of one another, hence are able to be completed in any order . A total of 3 machines exist within the factory and the associated resource limit of each machine is given in Table 3. The objective is to find an optimal schedule for all 7 jobs such that the make-span of the 3 machines is minimised without overloading them.

Table 2 Jobs to be scheduled

Job ($j\in J$)	Duration in days (D_j)
1	6
2	14
3	7
4	8
5	9
6	12
7	8

Table 3 Machine capacities

Machine ($i\in I$)	Capacity (L_i)
1	3
2	2
3	2

The model is programmed on AMPL [14] and solved using CPLEX [15]. The optimal schedule is given in Table 4. The optimized make-span is given as 18.8 days. It can be noticed that Machine 1 gets assigned to perform the jobs constituting the longest sum of duration. All three machines are utilised to satisfy the resource requirements.

Table 4 Machine schedule

Machine ($i \in I$)	[Job j, finish time f_j]
1	[1, 6], [4, 12.4], [7, 18.8]
2	[2, 18.8], [3, 7]
3	[5,9], [6,18.8]

The final schedule yielded was compared with one derived by an experienced engineer; the optimised schedule was found to have yielded a make-span that is 63% shorter than that suggested by the engineer.

Even though the machine scheduling problem is inherently NP hard [16], the solving times are expected to remain reasonable if the instance sizes are not large. This is particularly true when developing schedules for set periods (often conducted on a daily basis, instead of having a prolonged schedule covering the entire project's schedule) as is common on the shop floor of modular construction firms.

4 Conclusion

In this study, a framework of a DSS for scheduling operations on the factory floor of modular construction firms was proposed. The framework is comprised of three distinct modules, namely the Scheduling Unit, a simulator and a set of triggers that impact work conditions. A MIP model was also presented to solve the last stage of the optimisation scheduling problem within the Scheduling unit. The model is formulated as a parallel machine scheduling problem due to its inherent similarity with the characteristics of the scheduling operations in modular construction. The model was applied to a practical case study, and the resulting schedule was contrasted with one obtained based on the expertise of an engineer. Results showed that the model produces a schedule with a make-span that is 21% shorter in duration compared to that based on experience.

Only a single iteration of the DSS was presented in this paper. To be able to use the full DSS on large instances, a suitable heuristic that embeds the proposed optimisation model needs to be developed. This is currently being developed by the authors.

References

[1] S. C. Weber, *Scheduling Construction Projects: Principles and Practices*. Pearson Prentice Hall, 2005.

[2] M. Arashpour, R. Wakefield, N. Blismas, and T. Maqsood, "Autonomous production tracking for augmenting output in off-site construction," *Autom. Constr.*, vol. 53, pp. 13–21, May 2015.

[3] Alistair G.F. Gibb, *Off-site Fabrication: Prefabrication, Pre-assembly and Modularisation*. Wiley, 1999.

[4] L. Jaillon and C. S. Poon, "The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector," *Autom. Constr.*, vol. 18, no. 3, pp. 239–248, May 2009.

[5] J. S. Goulding, F. P. Rahimian, M. Arif, and M. D. Sharp, "New offsite production and business models in construction: priorities for the future research agenda," *Archit. Eng. Des. Manag.*, vol. 11, no. 3, pp. 163–184, May 2015.

[6] D. M. Gann, "Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan," *Constr. Manag. Econ.*, vol. 14, no. 5, pp. 437–450, Sep. 1996.

[7] C.-H. Ko and S.-F. Wang, "Precast production scheduling using multi-objective genetic algorithms," *Expert Syst. Appl.*, vol. 38, no. 7, pp. 8293–8302, Jul. 2011.

[8] W. T. Chan and H. Hu, "Constraint programming approach to precast production scheduling," *J. Constr. Eng. Manag.*, vol. 128, no. 6, pp. 513–521, 2002.

[9] J. O'Brien and F. Plotnick, *CPM in Construction Management, Eighth Edition*. McGraw Hill Professional, 2015.

[10] R. M. Lawson, R. G. Ogden, and R. Bergin, "Application of modular construction in high-rise buildings," *J. Archit. Eng.*, vol. 18, no. 2, pp. 148–154, 2011.

[11] D. Y. Eroglu, H. C. Ozmutlu, and S. Ozmutlu, "Genetic algorithm with local search for the unrelated parallel machine scheduling problem with sequence-dependent set-up times," *Int. J. Prod. Res.*, vol. 52, no. 19, pp. 5841–5856, Oct. 2014.

[12] K. Li and S. Yang, "Non-identical parallel-machine scheduling research with minimizing total weighted completion times: Models, relaxations and algorithms," *Appl. Math. Model.*, vol. 33, no. 4, pp. 2145–2158, Apr. 2009.

[13] C. M. Joo and B. S. Kim, "Hybrid genetic algorithms with dispatching rules for unrelated parallel machine scheduling with setup time and

production availability," *Comput. Ind. Eng.*, vol. 85, pp. 102–109, Jul. 2015.

[14] R. Fourer, D. Gay, and B. Kernighan, *Ampl*, vol. 119. Boyd & Fraser, 1993.

[15] IBM Knowledge Center, "IBM ILOG CPLEX Optimization Studio V12.6.0 documentation," 2016. [Online]. Available: http://www.ibm.com/support/knowledgecenter/SSSA5P_12.6.0/ilog.odms.studio.help/Optimization_Studio/topics/COS_home.html. [Accessed: 16-Oct-2016].

[16] J. K. Lenstra, A. H. G. Rinnooy Kan, and P. Brucker, "Complexity of Machine Scheduling Problems," in *Annals of Discrete Mathematics*, vol. 1, E. L. J. P.L. Hammer B. H.Korte and G. L.Nemhauser, Ed. Elsevier, 1977, pp. 343–362.