Crew allocation system for the masonry industry

Laura Florez*

Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE18ST, UK

Abstract: *Masonry construction is labor-intensive. Processes require a large number of crews made up of masons with diverse skills, capabilities, and personalities. Often crews are re-assembled and the superintendent in the site is responsible of allocating crews to balance between the complexity of the job and the need for quality and high production rates. However, the masonry industry still faces increased time and low productivity rates that result from inefficiencies in crew allocation. This article presents a system for efficient crew allocation in the masonry industry formulated as a mixed-integer program. The system takes into consideration characteristics of masons and site conditions and how to relate these to determine the proper crew for the proper wall to increase productivity. With the system, superintendents are not only able to identify working patterns for each of the masons but also optimal crew formation, completion times, and labor costs. To validate the model, data from a real project in the United States is used to compare the crew allocation completed by the superintendent on-site with the one proposed by the system. The results showed that relating characteristics of workers with site conditions had a substantial impact on reducing the completion time to build the walls, maximizing the utilization of masons and outlining opportunities for concurrent work.*

1 INTRODUCTION

Human resource allocation is the process of assigning crews of workers to tasks (Al-Bazi and Dawood, 2010). Tasks may require several crews with diverse functions to be completed and crews need to be scheduled to ensure an efficient output and adequate control (Hassanein and Melin, 1997). This process of planning workforce is one of the most difficult problems a company faces. Defining when workers should be hired and when these workers should work make workforce planning a challenging task (De Bruecker et al, 2015). Workers unlike other resources have many distinct and special characteristics that make the decision environment dynamic and managers have to deal with a very heterogeneous set of workers (De Bruecker et al, 2015). When workers are involved, companies not only must take into account labor needs but also workers characteristics and requirements (Van den Bergh et al 2013).

Multiple techniques have been used to solve scheduling and allocation problems such as integer programming (Ipsilandis, 2007; Elazouni and Gab-Allah, 2004), multi-objective optimization (Thiel, 2008; Gao et al, 2012; Koo et al, 2016), genetic algorithms (Adeli and Kumar 1995; Al-Bazi and Dawood, 2010; Ponz-Tienda et al, 2015), simulation-based optimization (Horn et al, 2007; Chen and Shahandashti, 2009), stochastic simulation (Maxwell et al, 1998), dynamic programming (Dück et al, 2012), ranking methods (Lin 2011), tabu search algorithms (Erdogan et al, 2010), fuzzy models (Shahhosseini and Sebt, 2011), meta-heuristics (Caprara et al 1998; Yunes et al, 2005; Debels et al, 2006), goal programming (Chu, 2007), non-linear programming (Klanšek, 2015), and stochastic programming (Morton and Popova, 2004; Lu et al, 2008).

These techniques have been used in various applications for construction scheduling. Adeli and Karim (1997) presented a general formulation for the sheduling of construction projects using a non-linear optimization approach providing the capabilities of the critical path method and linear scheduling methods for multiple construction applications. Al-Bazi and Dawood (2010) presented a strategy to allocate crews of workers in the precast concrete industry using genetic algorithms-based simulation modeling. Hegazy and Wassef (2001) developed a model for scheduling and cost optimization of repetitive construction projects by integrating the critical path and line of balance methods. This work was later extended by Hegazy and Kamarah (2008) with a model that uniquely represents core activities for high-rise construction projects. Gunnar (2011) developed a scheduling approach based on singularity functions for linear construction projects. Lin (2011) proposed a decision-making model for human resource allocation in remote construction projects. Lim et al (2014) presented a construction scheduling simulation algorithm to overlap activities. El-Rayes and Moselhi (2001) developed an optimization model that uses dynamic programming for repetitive construction projects. Yi and Chan (2014) developed an optimal work pattern for construction workers in high rise buildings. Maxwell et al (1998) presented a stochastic simulation program to find the optimal crew configuration using activity-based costing for construction exavations. Karim and Adeli (1999a) presented an information model for construction scheduling, cost optimization and change order management with its acompanion paper (Karim and Adeli, 1999b). Senouci and Derham (2008) developed a genetic algorithm-based multi-objective optimization model for scheduling linear construction projects. Damci et al (2013) proposed a genetic algorithm model for schedules established by the line of balance methodology for pipe line projects. Koo et al (2016) developed a multi-objective optimization model for vertical transportation of lift cars for workers in a skyscrapper construction. A review of the aspects and modelling approaches in personnel allocation in construction can be found in Brucker et al (2011), Zhou et al (2013) and Faghihi et al (2015).

However, despite this large body of work on the use of models for labor allocation and scheduling and certain applications for construction related decision making, there is limited literature including reports on the use of a system for labor allocation for the masonry industry. This study aims to expand the set of decision-making tools available to masonry contractors for scheduling and allocation of masons and propose a model that combines both technical methodologies as well as real life implications in masonry construction. In other words, a model based on sound technical methods that helps contractors allocate labor, while considering workers characteristics and site realities.

In this article, a system was developed to efficiently allocate crews of workers to the masonry industry. In masonry, there is a high demand of skilled workers and typically masons possess very specific characteristics and attributes. Additionally, masons work very closely to coordinate when to raise the line to build a course which results in constant interactions and interrelationships between the workers in a crew. Therefore, a proper allocation model would be a system that considers characteristics of masons and how to relate these characteristics and site conditions to select the proper crew for the proper wall to ensure minimum time and increased productivity.

This article is organized as follows. Section 2 discusses previous theories concerning crew allocation and scheduling. Section 3 describes the problem and specifics of the masonry industry. Section 4 presents the crew allocation system for the masonry industry. Section 5 presents a real life case study to validate and showcase the capability of the allocation system. Finally, Section 6 concludes the article and discusses opportunities for future research.

2 LITERATURE REVIEW

Crew allocation and scheduling has been extensively studied in construction. Some approaches to solve this problem have been developed for multiple applications such as high rise buildings (Hegazy and Kamarah, 2008; Yi and Chan, 2014; Arditi et al, 2002), linear projects (Senouci and Derham, 2008; Arditi and Bentotage, 1996; Gunnar, 2011), repetitive projects (El-Rayes and Moselhi, 2001; Hegazy and Wassef, 2001), housing and residential buildings (Nassar, 2005), precast concrete (Al-Bazi and Dawood 2010), remote projects (Hegazy and Kamarah, 2008; Lin, 2011), earth moving operations (Maxwell et al, 1998; Mohseli and Alshibani, 2007), multi-site projects (Lu et al, 2008), bridge construction (Marzouk et al, 2007), and highway construction (Adeli and Karim, 1997; Ioannu and Yang, 2016). A number of researchers have investigated the crew allocation problem, included but not limited to Biruk and Jaskowski (2008) who used a Petri-Nest approach to find the optimal allocation of subcontractors to execute repetitive processes. El-Gafy (2006) proposed an ant colony optimization algorithm to perform resource allocation for construction projects with repetitive activities. The algorithm considers precedence relations, unique skills for the resources and limitations on the number of resources. Nassar (2005) developed a genetic algorithm model to optimally assign crews to repetitive construction projects. Crew formation size is considered as the main parameter to optimize the project duration. Bhoyar and Parbat (2014) proposed a scheduling model for repetitive construction projects considering multiple crews that considers precedence relations and crew availability while minimizing the project duration and maximizing crew work continuity. Moselhi and Alshibani (2007) proposed a crew optimization model that combines genetic algorithm with spatial technologies to select optimal crew configurations. The model accounts for available resources and reconfigures crews while site operations are in progress. Francis Siu et al (2015) proposed a crew-job allocation model to facilitate resource management for both project and workface levels. Al-Bazi and Dawood (2010) presented a strategy to allocate crews of workers in the precast concrete industry using genetic algorithms-based simulation modeling. This work was later extended (Al-Bazi and Dawood, 2017) in a model that optimizes costs of resources while considering different crew allocation constraints such as skills of workers, crew formation details and the parallel repetitive layout of manufacturing operations. Other models have considered the different characteristics and attributes that workers may possess. The attributes of workers and how they relate to site conditions is crucial when considered in the allocation and scheduling analysis in construction to ensure the optimal utilization of each crew member. Studies have considered competency requirements (Shahhosseini and Sebt, 2011), proformance measurement (Lee et al, 2011; Liu and Wang (2010) mixed skills (Cai and Li, 2000), learning rates (Arditi et al, 2001), multi-skilled workers (Arashpour et al, 2016), levels of experience (Ahmadian Fard Fini et al, 2016). A comprehensive review of models and solution techniques for workforce scheduling can be found in Alfares (2004) and Van den Bergh et al (2013). De Bruecker et al (2015) most recently presented a state of the art review of allocation models incorporating workers' characteristics and skills.

2.1 Essential concepts

In this study, skills is defined as the ability of a worker to perform certain tasks well (De Bruecker et al, 2015). There are two different skill classes: the hierarchical class and the categorical class. In the case of hierarchical skills, workers with a lower skill level can do less than workers with a higher skill level. Workers with a higher skill level are more educated or have more experience and therefore can perform tasks faster. Some researchers have only used two levels of skills: unskilled and skilled (Corominas et al, 2008; Lagodimus and Leopoulos, 2000) while other researchers have used varying levels of skills (Süer and Tummaluri, 2008; Srour et al, 2006). In the case of categorical skills, each specific task requires a specific skill or set of skills. There is no difference in skill level, so the skills of one worker are not higher or lower than the skills of another worker. Instead, the skills that a worker has can determine which tasks the worker can perform. Some workers have one or more skills and a worker who posseses different categorical skills is referred to as a multi-skilled worker (Gomar et al, 2002; Florez et al, 2013) or a cross-trained worker (de Matta and Peters, 2009; Li and Li, 2000).

When the workforce is multiskilled, workers perform several different tasks. Some studies have found that workers usually work faster when working on their core task than when working on a task that differs from their core task. Placing workers on their core tasks has proven successful to increase workers' efficiency and performance. Benefits have been observed with regards to increase in the quality of the job (Batta et al, 2007; Tiwari et al, 2009), increase in speed (Huang et al, 2011; Tiwari et al, 2009), and a decrease in costs (Corominas et al, 2012; Brunner et al, 2011). Due to this varying levels of efficiency, a worker is said to be more suitable to work in certain tasks than in others. Note that the suitability of a worker to work in a certain task is not related to the level of experience of that worker, but rather to the worker's specialty that allows the worker to perform faster in the core task (De Bruecker et al, 2015).

For tasks requiring two or more workers to work together, compatibility is a measure that determines the relation a worker has with his co-workers and the way they work together (Nussbaum et al 1999; Kumar et al, 2013). Compatibility should be considered to make an appropriate worker assignment because teams of workers that work well together are critical to work success and effectiveness. In other words, teams of workers that are compatible may reduce potential noncooperation or conflict (Lin et al, 2012) resulting in an increase in the performance of a group (Nussbaum et al 1999).

The above literature presented essential concepts and definitions that have been used in a number of crew allocation problems. Some studies have considered the skills of the workers but have not considered site conditions and how to relate these to optimally assign workers to tasks. Other systems have considered the personality of the workers but have not considered the interaction between different workers and how it can affect the performance when workers are grouped in crews. In addition, some studies have presented only technical methodologies but have not considered real life implications in masonry construction. This study aims to expand the set of decision-making tools available to masonry contractors for the scheduling and allocation of masons. The developed system presented in this article supports decision makers to place the proper crew for the proper wall while minimizing the total time to complete the walls. The next section describes the intrinsic characteristics of the masonry industry.

3 MASONRY CONSTRUCTION

Masonry construction is labor-intensive. Processes involve little to no mechanization and involve crews made up of workers with diverse skills, capabilities and personalities. Tasks may require several crews to complete different tasks, and crews need to be scheduled to ensure an efficient output and adequate control (Hassanein and Melin, 1997). To detail masonry jobsites, two sections, namely characteristics of masons and conditions in masonry sites describe typical attributes of masons and characteristics of walls to explain how these can be related so that a proper allocation of workers can be completed.

3.1 Characteristics of masons

Through extensive site observations and interviews with masonry practitioners across the United States, it was found that typically superintendents in the U.S. masonry industry use workers' information and specific criteria for designing crews. These criteria serve as guidelines in the jobsite for grouping workers and forming the most efficient crew to build a wall. Three criteria for designing crews that impact productivity were found: compatibility, suitability, and craft. The reader is referred to Florez (2015) for a detailed description of the results from the observations and interviews.

3.1.1 Compatibility

Masons have different personality characteristics and behavioral patterns and this may influence the type of interactions that occur among the workers in a crew. Some masons work well together, but some masons do not work well with other masons. In most cases when there is conflict in a crew, the motivation of the workers is lowered which in turn decreases the productivity of the crew (Nussbaum et al, 1999). Therefore, an adequate mix of personalities is needed to ensure that the masons in a crew can establish healthy relationships to maintain a high level of productivity. During the site visits and interviews it was found that superintendents try to group masons in crews in which the masons get along very well, that is, masons that can establish healthy relationships and have a compatible personality. By grouping masons that get along well, superintendents aim to maximize production.

3.1.2 Suitability

Masons have different specialties and as a consequence are more suitable to work in one type of wall rather than another. Some masons are very good leveling and plumbing and therefore are very efficient working on wall sections that require a high demand of technical work (e.g. openings, intricate corners, details, building leads, and penetrations). These are often referred to as technical masons. Other masons are not very fast with the level and the plumb but are very efficient working in wall sections that require non-technical work (e.g. straight walls or walls with little to no openings). These are often referred to as non-technical masons. During the site visits and interviews it was found that superintendents try to assign masons to wall sections that match the suitability of the mason with the type of wall. In other words, to increase productivity superintendents assign a technical mason to a detailed wall and a non-technical mason to a non-detailed wall.

3.1.3 Craft

Masons know how to lay brick and block but are usually more efficient and produce higher quality work with units of one craft rather than another. Some masons are good at handling smaller units and are more detailed so they are better brick layers, whereas some others are stronger and are better at laying block. That is, in masonry there are bricklayers and there are block masons. During the site visits and interviews it was found that superintendents assign bricklayers to brick walls and block masons to block walls to increase production.

3.2 Conditions in masonry sites

The extensive site observations and interviews with masonry practitioners also pointed out that there are site conditions that may influence the allocation of masons. The geometric characteristics of walls as well as the masonry unit of the wall may impose specifications on which is the proper mason for the proper wall.

In masonry, walls can be categorized by two degrees of difficulty: easy/normal and difficult. In a similar manner to the characterization used by the National Electrical Contractors Association (NECA) for characterizing the job degree of difficulty to install electrical components (NECA, 2015), masonry walls can be categorized in two degrees. With such a categorical system, the wall's degree of difficulty may help determine the total number of masons, the type of masons and the characteristics of the masons required to build a specific wall. This facilitates the planning process since masonry contractors can use the system to estimate the number and characteristics of workers needed to complete a project. The proposed two degree wall characterization for masonry is detailed below.

3.2.1 Easy/normal

An easy/normal wall is the most common type of wall in a masonry project (see Figure 1). It is a straight wall with no openings or just a few openings such as doors, window frames, and intricate for ductwork. The spacing between the openings (if there are) ranges between 15 ft. and 20 ft. Because it is a line and there are no/few openings, it is built using a string line. Since there is no difficulty in this wall, it is the fastest wall to build and the highest productivity rates are expected for this type of wall. To build an easy/normal wall typically the superintendent assigns a mason that is very fast with non-technical work, that is, a mason that is fast building a wall with a string line and does not need to constantly level and mark cuts and details.

3.2.2 Difficult

A difficult wall is a wall that has mostly detailed and technical work such as openings, intricate corners, details, leads, and penetrations (see Figure 2). This type of wall may involve building arches, piers, windows, columns, as well as placing color brick units. The spacing between the openings can be as small as 1 ft. Because of its shape and the amount of openings and details it has, it can't be build using a fixed string line. It is built by constantly leveling and plumbing the wall with the plumb rule and level. Since there is some difficulty in this wall, it requires a high level of technical work. It is the slowest wall to build and the lowest productivity rates are expected for this type of wall. To build a difficult wall, typically the superintendent assigns a mason that has expertise in technical work, that is, a mason that builds walls with the plumb rule and level and has experience in marking cuts and details. The next section presents the crew allocation system.

Figure 1 Easy/normal wall

Figure 2 Difficult wall

4 CREW ALLOCATION SYSTEM

Crew scheduling in masonry construction is the process of configuring crews and allocating crews to the different tasks. Crew scheduling in a masonry site is typically done as described below. Every week the project superintendent along with the project manager, determine the walls that are going to be built based on the areas that are available for the masonry work specified by the general contractor. Once the walls are established, the superintendent determines the number of masons to complete the walls considering the man-hour needs specified in the estimate, the size of the walls, and the workload. After the number of masons is established, the superintendent determines which masons are going to be grouped in a crew to work on each wall or wall section. Every time a crew finishes building a wall, the superintendent either assigns the crew to a different wall or re-configures the crew and assigns the new crew to another wall. This crew makeup and allocation process continues for the whole duration of the project. In other words, every week the superintendent plans the labor requirements for the project based on the areas that are available for the masonry work.

In the current allocation strategy performed on-site, superintendents know the characteristics and attributes of their masons “in their head” and usually use common sense to allocate masons and crews to walls after testing different staffing options. In other cases, superintendents have a rating system to rank their masons so they know which masons are the “best” and which are “not so good”. However, both practices do not account simultaneously for the different characteristics of masons (compatibility, suitability, and craft) and how these can be linked to site conditions to optimize the allocation of crews. As described in Section 3, not every mason can be assigned to every crew and not every crew can be assigned to every wall; a successful project is one in which the right person is selected for the right job (Palaneeswaran and Kumaraswamy, 2000).

To address this problem, this study presents the masonry construction industry with a system designed to facilitate the crew makeup and allocation process. The system considers the complexities of the workforce, the characteristics of the site, and the social interactions between masons to support superintendents for allocating crews in masonry.

4.1 Model formulation

The proposed model can help masonry superintendents design optimal crews while considering labor needs, availability of workers, and wall requirements. The model determines which crew is assigned to which wall, the times that each crew and consequently eash mason is working and the times to start building the walls.

The formulation includes the set of walls I, the set of crews J, and the set of masons R. The set J_r contains the crews with mason r, while the set J_i contains the crews capable of building wall i. The formulation also includes a set of precedence relations between the walls, A. That is, if wall $i \in I$ precedes wall, $i' \in I$ then $(i, i') \in A$.

The model also includes parameter q_i representing the number of masons needed to construct wall i whereas parameter p_j represents the number of masons in crew j. Parameter v_{ij} represents the number of time periods required to complete wall i with crew j. Parameter c_j^{wage} represents the wage (per period of time) of crew j.

Parameter b_t represents the available budget for time t. The binary parameter a_{jt} takes the value of 1 if crew j is available in time t; it takes the value of 0, otherwise.

The structural binary variable x_{ijt} takes the value of 1 if crew j is assigned to wall i at time t; it takes the value of 0, otherwise. The binary variable y_{ijt} takes the value of 1 if wall i is assigned to crew j and scheduled to start at the beginning of time t; it takes the value of 0, otherwise. In addition the (auxiliary) binary variable z_{ij} takes the value of 1 if wall i is assigned to crew j; it takes the value of 0, otherwise. The binary variable r_{it} takes the value of 1 if wall i is scheduled to start at the beginning of time t; it takes the value of 0, otherwise. Variable $\overline{w}_t$ represents the number of masons working in the scheduled walls at time t (where $\overline{w}_0 \equiv 0$). The auxiliary variable $\overline{c}_t^{labor}$ denotes the labor cost incurred at time t. The decision variable $C_{\max}$ represents the completion time of the latest wall in the project. The proposed mixed-integer program follows:

$$f_{1=} \min C_{\max} \quad (1)$$

subject to,

$$C_{\max} \geq (t + v_{i,j} - 1) \cdot y_{i,j,t} \quad i \in I, j \in J, t = 1,...,T \quad (2)$$

$$\sum_{t=1}^{T} \sum_{j \in J_i} y_{i,j,t} = 1 \quad , i \in I \quad (3)$$

$$\sum_{i \in I} x_{i,j,t} \leq 1 \quad ; j \in J, t = 1,...,T \quad (4)$$

$$\sum_{j \in J_r} \sum_{i \in I} x_{i,j,t} \leq 1 \quad ; t = 1,...,T, r \in R \quad (5)$$

$$z_{i,j} = \sum_{t=1}^{T} y_{i,j,t} \quad ; i \in I, j \in J \quad (6)$$

$$v_{i,j} \cdot z_{i,j} = \sum_{t=1}^{T} x_{i,j,t} \quad ; i \in I, j \in J \quad (7)$$

$$v_{i,j} \cdot y_{i,j,t} \leq \sum_{\hat{t}=t}^{t+v_{ij}-1} x_{i,j,\hat{t}} \quad ; i \in I, j \in J, t \in T \quad (8)$$

$$\sum_{i \in I} q_i \cdot x_{i,j,t} \leq a_{j,t} \cdot p_j \quad ; j \in J, t \in T \quad (9)$$

$$x_{i,j,t} \leq a_{j,t} \quad ; i \in I, j \in J, t \in T \quad (10)$$

$$y_{i,j,t} \leq a_{j,t} \quad i \in I, j \in J, t \in T \quad (11)$$

$$\overline{w}_t = \sum_{i \in I} \sum_{j \in J} x_{i,j,t} \cdot p_j \quad ; i \in I, t = 1,...,T \quad (12)$$

$$\overline{c}_t^{labor} = \sum_{j \in J} c_j^{wage} \cdot x_{i,j,t} \quad ; t = 1,...,T \quad (13)$$

$$\overline{c}_t^{labor} \leq b_t \quad ; t = 1,...,T \quad (14)$$

$$r_{i,t} = \sum_{j \in J_i} y_{i,j,t} \quad ; i \in I, t \in T \quad (15)$$

$$r_{i',t} \leq \sum_{j \in J} \sum_{\hat{t}=1}^{t-v_{i,j}} y_{i,j,\hat{t}} \quad ; (i,i') \in A, t \in T \quad (16)$$

$$x_{i,j,t} \in \{0,1\} \quad ; i \in I, j \in J, t \in T \quad (17)$$

$$y_{i,j,t} \in \{0,1\} \quad ; i \in I, j \in J, t \in T \quad (18)$$

$$z_{i,j} \in \{0,1\} \quad ; i \in I, j \in J \quad (19)$$

$$r_{i,t} \in \{0,1\} \quad ; i \in I, t \in T \quad (20)$$

$$\overline{w}_t \in Z_+^1 \quad , t = 1,...,T \quad (21)$$

$$C_{\max} \in Z_+^1 \quad (22)$$

$$\overline{c}_t^{labor}, b_t \geq 0 \quad , t = 1,...,T \quad (23)$$

As is shown in (1), the model seeks to minimize the total execution time when scheduling all the walls in a project. The group of constraints in (2) sets $C_{\max}$ to the completion time of the latest wall in the schedule. The set of constraints in (3) guarantees that every wall is built. The set of constraints in (4) guarantees a crew builds at most one wall at any given time while the set of constraints in (5) guarantees that a mason is not working in two crews at any given time. The set of constraints in (6) activates the corresponding z variables when a given wall is assigned to a crew. The set of constraints in (7) and (8) guarantee that a crew that is assigned to a wall stays in the same wall until the wall is finished. Note that a crew works during consecutive time periods for the whole duration of the wall, that is, no interruptions are allowed. The group of constraints in (9) guarantees that at any time, the available workforce is able to fulfill the demand of labor. The bound constraints in (10) and (11) guarantee that a crew assigned to a wall is a crew that is available. The expression in (12) denotes the number of masons working in time t. The expression in (13) denotes the labor cost in time t. The group of constraints in (14) guarantees that the labor cost does not exceed the available budget at any given time. The set of constraints in (15) articulates decision variables y with auxiliary variables r. The precedence conditions between walls are accounted for in (16). Variable-type constraints (17), (18), (19), and (20) define variables x, y, z, and r as binary. Constraints (21) and (22) define variables $\overline{w}$ and $C_{\max}$ as non-negative integers. Finally, constraint (23) accounts for non-negativity of $\overline{c}_t^{labor}$ and b_t.

4.2 Considering cost and time

To consider time and cost objectives, the model could be extended as a multi-objective mixed-integer programming problem. The multi-objective model can be solved using a priori lexicographic ordering of the objectives (Steuer, 1989), using a similar solution approach that has been applied in Florez et al (2013) and Villegas et al (2006). In contrast to methods designed to unveil a whole set of non-dominated solutions, this strategy first gives top priority to minimizing the time to complete the walls followed by minimizing the cost, without deteriorating the previously attained objective. The solution strategy is divided in two phases: in the first phase the objective of minimizing the time to complete the walls $f_1 = \min C_{\max}$ is solved in isolation subject to the set of constraints (1) to (23), referred as the solution space Ω. The optimal value for the first phase is called f_1^*. Note that in this objective while the time is minimized, there are no costs involved. Without being a minimum cost objective, it is possible to use more expensive crews without being absolutely necessary, giving rise to a more expensive schedule. By incorporating a second phase, the new schedule has the same completion time, but with a tighter schedule that penalizes (among others) useless crews. Aside from minimizing cost in $f_2 = \min \overline{c}_t^{labor}$ the second phase guarantees that the masonry project does not take longer than the schedule found earlier in the first phase. Thus, the model considers the same set of constraints defined in the solution space Ω and an additional constraint:

$$C_{\max} \le f_1^* \tag{24}$$

4.3 Model extensions

We could further extend the mathematical program defined in (1)-(23) to incorporate additional considerations. For instance, the cost of shifting masons between crews may impact the productivity of the crew since an increased variation of masons makes it difficult to coordinate work and crews that are stable may benefit from the learning curve (Burleson et al, 1998). In order to include the cost of shifting crew members around, a new objective function and constraints can be proposed similar to the ones in Ponz et al (2017). The new objective defined as the sum of differences of consecutive daily resources (SDCDR) aims to minimize the sum of fluctuations or absolute variation of resources along the planning horizon. In other words f_3 aims to stabilize the workforce and maintain (as much as possible) the same crew configurations. Let the cost of shifting crews be denoted by c^{shift}. The binary variable s_{jt} takes the value of 1 if crew j is shifted between times $t-1$ and t; it takes the value of 0, otherwise. The objective of maintaining stable crew configurations is given by equation (25):

$$\min f_3 = \sum_{t=1}^{T} \sum_{j=1}^{J} \left| s_{j,t} - s_{j,t+1} \right|^2 \tag{25}$$

To include the cost of shifting crews to the base model defined by (1)-(23), we add equations (25) and (26), and replace equation (13) by equation (27):

$$s_{j,t} = \sum_{i \in I} x_{i,j,t} \tag{26}$$

$$\overline{c}_t^{labor} = \sum_{j \in J} \left(c_j^{wage} \cdot x_{i,j,t} + c^{shift} s_{j,t} \right) \quad ; t = 1,\ldots,T \tag{27}$$

4.4 Productivity function

As shown in the model described in equations (1) to (23), the objective is to minimize the time. The time and consequently the productivity of a crew is affected by: how the masons in the crew get along and work well together (compatibility), how suitable the crew is to work in a specific type of wall (suitability), and how well the crew works with a type of material (craft) as described in Section 3.1. Therefore, it is assumed that productivity is affected by a productivity factor (p) and is a function of the compatibility (c_j), suitability (s_j), and craft (k_j) of a crew. The productivity factor for a crew is given by equation (28):

$$p = \tfrac{1}{3}\left(c_j + s_j + k_j\right) \tag{28}$$

A number of assumptions were used when determining the productivity factor. The purpose of these assumptions is to simplify the process of quantifying the characteristics of the masons and measure their impact on productivity. The assumptions are as follows:

- The superintendent can give a craft and suitability score for each crew member. Similarly, it can determine the compatibility score between each and every pair of masons.
- When a crew is formed, the compatibility, suitability and craft score of the crew is the minimum of the scores between the masons that are in the crew.
- The higher the compatibility, the suitability, and craft scores, the better the masons get along, work in a type of wall and work with a craft, respectively.
- The function is a linear approximation since it is anticipated that the three scores will contribute to affect the productivity. It is not the product of the scores because it is not expected that for a minimum variation these may have such a significant reduction in the productivity which does not truly reflect the capabilities of the masons.
- The coefficients of the three scores in the function are assumed to be equal since without any further information it is natural to propose that the scores influence the productivity equally. The productivity will be the mean value of the scores.

Note that the scores captured to quantify the productivity factor are similar to the rank given to the masons by superintendents in real projects. Additionally, note that the function was developed considering a medium size construction site. Therefore, further studies can be developed to verify any modifications on the type of function as well as the coefficients for each one of the scores.

4.5 Productivity and time

With the productivity factor given by equation (28), now let's look closer at how to use it to determine the number of time periods (parameter v_{ij}) that crew j takes to complete wall i. The number of time periods is a parameter and it is calculated for each possible crew, that is, every combination of masons. Assume the craft of the wall is 8-inch concrete block (CMU). The length and height in linear feet are known from the drawings of the project. Based on the number of openings (e.g. windows, door frames) and the amount of detailed work that is required to build the wall (e.g. cuts, arches), the difficulty for the wall is determined. In other words, the wall has been labeled by the superintendent as either an easy/normal wall or a difficult wall. Table 1 shows the information for wall 1.

In this case, wall 1 is an easy CMU block wall. Given the length and the height of wall 1 in linear feet and considering the nominal dimensions of an 8-inch block (8"x8"x16"), it can be determined wall 1 is 14 units long and has 12 courses (12 CMU units high). Based on the length of the wall and assuming that one mason is assigned every 15 linear ft. of wall (Florez 2015), two masons will be working on wall 1, that is, this wall will be built using a two-mason size crew. To calculate the productivity of a two mason crew, let's assume that the compatibility, suitability, and craft scores have been determined for every combination of masons. For instance, for mason 2 (m2) and mason 4 (m4) the scores are: suitability (s_j) = min{0.8, 0.8}=0.8; compatibility (c_j) = min{0.9}=0.9; craft (k_j) = min{0.8,0.8}=0.8)

Therefore, the productivity factor is given by:

$$p = \tfrac{1}{3}\left(c_j + s_j + k_j\right) = 0.83$$

Now let's calculate the productivity F for the crew composed of m2 and m4:

$$F = p \times n \times a$$

Where p is productivity factor for the crew, n is the number of masons in crew , a is the average productivity per day per mason.

Table1 Characteristics of wall 1

Craft	8-inch CMU block
Difficulty	Easy
No. masons	2
Length	18 ft.
Height	8 ft.
Total	168 units

Note that the average productivity per day per mason varies if it is for CMU block or for brick. The productivity for 8-inch block used in estimating masonry work is typically 100 units per day per mason while the productivity for brick is 500 units per day per mason (Florez, 2015). Hence, the productivity for the crew (number of units per day per crew) composed of mason 2 and mason 4 (considering the compatibility, suitability, and craft scores) for a block work is:

$$F = p \times n \times a = 0.83 \times 2 \times 100 = 166$$

Now let's calculate the time that it will take crew j to build wall 1: $v_{ij} = u_i / F$; where, v_{ij} is the time it takes crew j to build wall i; u_i is the total number of units in wall i, and F is the productivity of crew j. The time periods (days) that it will take the crew composed of m2 and m4 to build wall 1 is 1.10. In other words, it will take m2 and m4 two days to build wall 1.

5 CASE STUDY

This case study is based on a real 14 story apartment building with an area of 20,000 ft^2 in Michigan, United States. The floor division of the building is as follows: there is a basement with an underground parking garage; the first floor houses a multi-flex space, the second floor through the fourteenth floor has units with a variety of floor plans including one, two, three, and four bedrooms. The floor height is about 9 feet and 2 inches. The façade of the building has color brick (dimension 4”x4”x12”) and there are interior columns and walls that are also made up of color brick in the first and second floors.

The objective of the case study was to compare the allocation on site performed by the superintendent against the model’s allocation to determine whether there was any difference in the schedule and test the impact of the model. To perform the comparison, the allocation and schedule of the masons as well as the labor productivity were documented on-site during a week in October 2015. During the week, the project superintendent performed the allocation of the masons and this was recorded. All relevant data to run the model were collected by interviewing the superintendent and the contractor. Finally, the allocation on-site was compared with the model’s solution.

5.1 Input parameters

The contractor and superintendent determined the walls that had to be built and the precedence relations between the walls for the apartment building. It was considered that each wall was a segment that extended from one corner to another corner. Nine walls had to be built and they ranged from 20 ft. to 60 ft. in length. The masons started on the east side of the building, continued on the south, then north, and finally on the west side of the building.

The precedence relations between the walls are detailed in Figure 3. Note that wall 4 can only be built if wall 1, wall 2, and wall 3 are finished. In a similar manner wall 7 can only be built if wall 4, wall 5, and wall 6 are finished. This implies that wall 1, wall 2 and wall 3 are also finished by the time wall 7 is started. The nine walls had the characteristics detailed in Table 2 and these were provided by the superintendent and the project drawings.

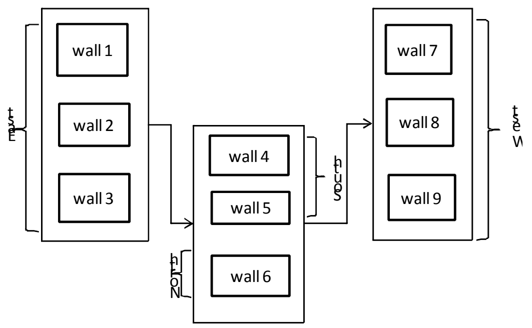

Figure 3 Precedence relations between the walls

The difficulty of a wall was either determined as easy/normal (E) or difficult (D) and was based on the number of openings and details in each wall. The building only had brick hence the craft was brick. The number of masons was the actual manpower allocated by the superintendent and used on-site to build the walls during the week in the Fall 2015.

Note that for the purpose of the comparison the number of masons used was as it happened on-site. The dimensions of the walls and number of units were calculated using the drawings of the building. Based on the workload for the week, the superintendent determined that six masons were needed to work on the nine walls (m1, m2, m3, m4, m5, m6). The supply had no variations in the number of masons so there were six masons available during the entire week and 64 possible crew formations. During the week, the nine walls were built with crews of one, two, and three masons, so there were only 41 possible crew formations (see below).

One mason: c1:{m1}; c2:{m2}; c3:{m3}; c4:{m4}; c5:{m5}; c6:{m6}
Two masons: c7:{m1, m2}; c8:{m1, m3}; c9:{m1, m4}; c10:{m1,m5}; c11:{m1,m6}; c12:{m2,m3}; c13: {m2,m4}; c14:{m2,m5}; c15:{m2,m6}; c16:{m3,m4}; c17: {m3,m5}; c18: {m3,m6};c19{m4,m5}; c20: {m4,m6}; c21: {m5,m6}
Three masons: c22:{m1,m2,m3}; c23:{m1,m2,m4}; c24:{m1,m2,m5}; c25:{m1,m2,m6}; c26:{m1,m3,m4}; c27:{m1,m3,m5}; c28:{m1,m3,m6}; c29:{m1,m4,m5}; c30:{m1, m4,m6}; c31:{m1, m5, m6}; c32:{m2, m3,m4}; c33:{m2, m3,m5}; c34:{m2, m3, m6}; c35:{m2, m4,m5}; c36:{m2,m4,m6}; c37:{m2,m5,m6}; c38:{m3, m4,m5}; c39:{m3,m4,m6}; c40:{m3, m5,m6}; c41: {m4, m5,m6}

After the information of the walls was compiled, the superintendent was given a brief explanation of the scores. To obtain the scores, the superintendent was provided with a table to fill in the scores in a similar manner to the ranking he gives to his masons. For the six masons, the superintendent provided information on the suitability, the craft, and the compatibility scores. The scores provided for each of the masons were based on the knowledge the superintendent had about the masons’ performance from previous works and their characteristics. Table 3 shows the compatibility scores. For simplicity, the superintendent was asked to state how well the masons get along: not very well, well, excellent. Based on the responses of the superintendent, a compatibility score between masons was determined (0.1=not very well, 0.5=well, 0.9=excellent). The scores were taken similarly to a Likert-scale, that is, the responses were scaled so that the distance on each item is equal.

Table 2 Characteristics of the nine walls

Walls	w1	w2	w3	w4	w5	w6	w7	w8	w9
Difficulty	D	E	D	D	E	D	D	E	D
No. masons	2	2	2	1	2	3	2	2	2
Length (units)	35	30	27	33	35	46	37	60	30
Height (units)	27	27	27	27	27	27	27	27	27
Total units	945	810	729	891	945	1242	999	1620	810

For the suitability score, the superintendent was asked to score the masons on a scale from 0 to 1 based on the information he had about each mason from previous work and productivity rates working on easy/normal walls and difficult walls.

Table 3 Compatibility score for masons

Mason	m1	m2	m3	m4	m5	m6
m1	-	0.5	0.9	0.5	0.9	0.5
m2	0.5	-	0.5	0.5	0.5	0.9
m3	0.9	0.5	-	0.1	0.9	0.1
m4	0.5	0.5	0.1	-	0.9	0.5
m5	0.9	0.5	0.9	0.9	-	0.5
m6	0.5	0.9	0.1	0.5	0.5	-

Table 4 shows the scores provided by the superintendent for the six masons that were available on the site. Note that the suitability is directly related to the specialty of the mason. Similarly, the superintendent was asked to provide a craft score for the masons on a scale from 0 to 1 based on the information he had about each mason from previous work experience working with brick and block walls. Table 5 shows the scores provided by the superintendent for the six masons that were available on the site.

Table 4 Suitability score for masons

Mason	Easy/Normal	Difficult
m1	0.8	0.5
m2	0.6	0.7
m3	0.4	0.8
m4	0.9	0.5
m5	0.6	0.9
m6	0.9	0.7

Finally, the input parameters include the time that each crew will take to build a wall. The time (parameter v_{ij}) was calculated using the scores that the project superintendent provided (Table 3 to Table 5). Time periods are measured in hours and it was assumed that the weight of the three factors (compatibility, suitability, and craft) is equal, that is, each one equally affects the productivity of the crew.

Table 5 Craft score for masons

Mason	Block	Brick
m1	0.8	0.7
m2	0.6	0.8
m3	0.8	0.9
m4	0.9	0.7
m5	0.8	0.6
m6	0.9	0.6

5.2 Optimal allocation of crews

The allocation and schedule of the crews performed by the superintendent on site and the model are displayed in several figures below. Figure 4 illustrates the working pattern for each crew (site) and the optimal timing of the walls. For instance, crew 21 works in wall 2 from time period 1 until time period 10. In time period 29, the crew is regrouped and starts working in wall 9 in time period 29 until time period 37. Note that the completion time of the latest wall in the schedule (wall 8) is time period 41. Note that wall 1, wall 2, and wall 3 were completed before any other wall could start. In a similar manner, wall 4, wall 5, and wall 6 were completed before the next three walls (wall 7, wall 8, and wall 9) started. As shown in Figure 4, the schedule only allows *go-no-go* decisions, that is, walls were not partially built and once they are in progress are not interrupted.

Figure 5 illustrates the working pattern for each crew and the optimal timing of the walls (model). Note that the completion time of the model is time period 41. For instance, crew 15 works in wall 1 from time period 1 until time period 10. In time period 30, the crew is re-grouped and starts working in wall 9 until time period 39. Note that the report shows when a mason is working in a wall (productive time) and when the mason is not productive.

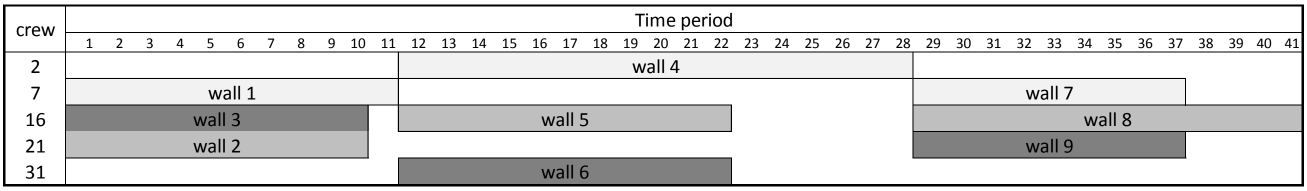

Figure 4 Report per crew and schedule (site)

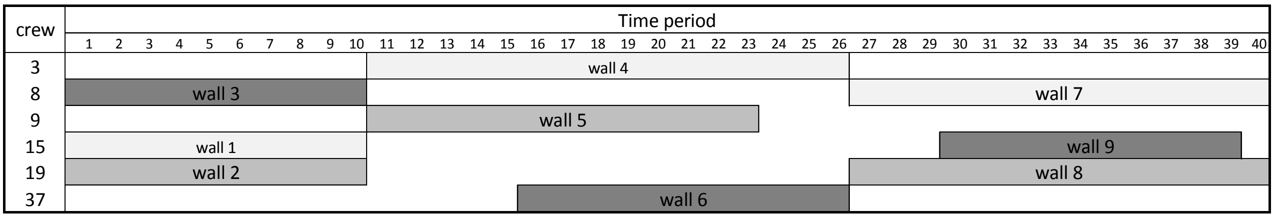

Figure 5 Report per crew and schedule (model)

The results show that the schedule of masons in the site was very similar in terms of time as that of the model. There are some aspects that can be observed by looking in more detail at the results. First, the allocation of the model suggests that some masons are underutilized. For instance, the model shows that between time period 11 and time period 15, crew 37 (mason 2, mason 5 and mason 6) is not assigned to a wall. Therefore, these masons can be allocated to another wall or can be assigned to a different task such as placing waterproofing, flashing and drip edge components, wall ties, and termination bars.

Second, the productivity score of the crews used on site was 0.52 and that of the crews suggested by the model was 0.74. Note that the difference in the productivity score for the site and the model, while it did not produce a significant increase in productivity, it led to a reduction of one time period. Note that the latest wall (wall 1) for the first group of walls is built by crew 7 on-site (c_j=0.5, s_j=0.5), while the model suggests using crew 15 (c_j=0.9, s_j=0.7). Both crews have the same craft score, but the difference of scores in compatibility and suitability result in a difference of one time period.

Third, the superintendent used crew 16 to build wall 3, wall 5, and wall 8, and crew 21 in wall 2 and wall 9. The model suggested using repeatedly crew 15 in wall 1 and wall 9, and crew 19 in wall 2 and wall 8. In other words, the superintendent made fewer changes in the configurations of the crews than those suggested by the model. This result suggests that the superintendent may prefer to keep the same crew configurations. However, the compatibilities of crew 16 (0.1) and crew 21 (0.5) is low compared to other crew configurations that work well together with blocks and also have a good working environment such as crew 19 (0.9) and crew 8 (0.9). Finally, it has to be noted that even though the data collection process was not controlled, the results of the system are very close to what happened on the site and have served to compare the allocation of masons. These results show that the model truly reflects reality and can serve as a decision support system for superintendents.

5.3 Sensitivity Analysis

The primary goal of the proposed model is to minimize the time to complete the walls in a masonry project, selecting the proper mason for the proper wall and determining the working times for each of the crews. However, changes in project conditions such as budget and labor prices, number of workers and workers' availability' can affect the optimal solution. The study of the effect of these external changes will provide the superintendent and the contractor with valuable information to take better decisions under a constantly changing environment.

To illustrate how the solution for the case study changes under different conditions, let's consider that the wage per mason ranges from USD 15 to USD 25 per time period (RSMeans, 2017) and using the costs of masonry crews (RSMeans, 2017), the budget for labor cost was generated randomly, using the wage per mason and the number of masons. There are 6 masons available and nine walls (the same as the case study), and an available budget of USD 2,700 which is enough to reach the point C presented in Figure 6, where the completion time is 50 time periods. The compromise between budget and completion time is illustrated in Figure 6. Points A, B, show and opportunity to reduce the completion time with a relatively low effort in terms of cost. On the other hand, points D, E, F require a higher increase in cost to reduce the time. Each of these points represents the allocation of crews and the walls that each crew is going to build. For instance, point C corresponds to an allocation that takes 48 time periods, while point D represents a different crew allocation that reduces the completion time by four time periods compared to point C. This reduction from 48 time periods to 44 time periods implies using crew 12 to build wall 1 and crew 17 to build wall 7, but demands an addition of just USD 270 to the current budget. In contrast, moving from a solution represented by point D to point F (from 44 time periods to 40 time periods), implies a reduction of four time periods, but represents an addition of USD 1,530. It is worth mentioning that under higher budget levels, the model is not able to further reduce the completion time of the project, as shown by points E and F.

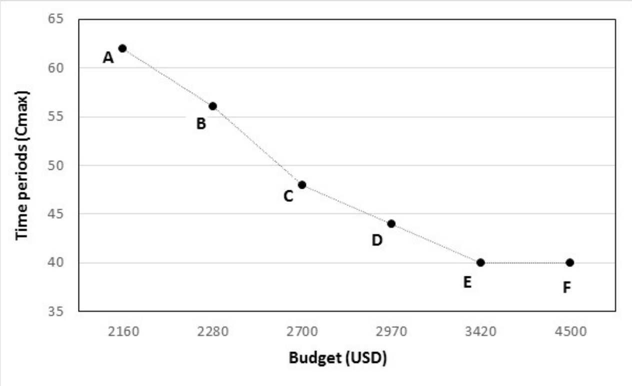

Figure 6 Existing tradeoff between time to complete projects and budget

The number of masons (and crews) can also affect the optimal solution. For instance, if the number of masons decreases by one, which seems to be a slight change, the time to complete the walls increases from 40 to 48. In contrast, note that if the number of masons increases by one, the completion time is the same for 6 masons and 7 masons. This increment from 6 to 7 does not reduce the time and adds the cost of an extra mason. Figure 7 can help superintendents determine the optimal number of masons for a given project by showing the compromise between the number of crews and the completion time.

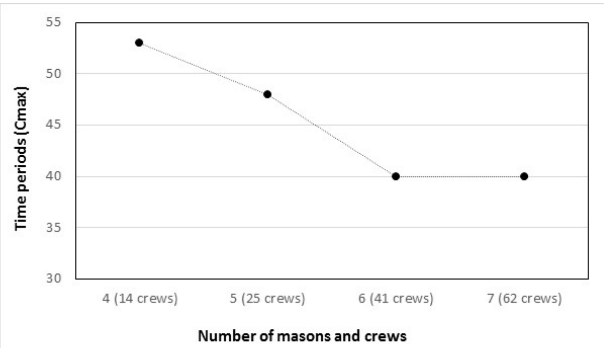

Figure 7 Existing tradeoff between completion time and number of masons

Another scenario is to have a supply of labor with variations per time period, reflecting changing availability of masons due to sickness or labor working in a different project. Let´s assume that mason 1 is not available in time period 2 and mason 2 is not available between time periods 10 to 13 and. In other words, all the crews with mason 1 are not available in time period 2 and similarly all crews with mason 2 are not available between time periods 10 to 13. Note that the completion time increases by one time period compared to the optimal time of the model. The limited availability of masons, forces wall 2 to be started in time period 3 since mason 2 is not available in time period 2.

Table 6 shows the results for the two phases in terms of the objectives sought (considering time and cost). Note that values in bold in the table denote the objective being optimized. Table 1 also shows the results relative to the best achievable value for each objective. For instance, when minimizing the cost, the decision-maker can achieve an optimal value of completion time equal to 40, while reducing the cost by 6.79%.

Table 6 Value of the objectives for the case study

	Objective function	
	Minimize time (phase 1)	Minimize cost (phase 2)
Completion time	**40 (100%)**	**40 (100%)**
Total expense	USD 4,074 (106.79%)	**USD 3,815 (100%)**

5.4 Model capabilities

We could further test the capabilities of the model and evaluate its performance by running a series of instances of a hypothetical problem. Based on the case study and the observations conducted on-site, 2 sets with a total of 18 instances have been generated by increasing the number of walls and the number of masons per crew. One set considers that all walls have to be built with 2-mason crews and the other set considers the walls have to be built with 3-mason crews. Let's assume each instance of each set is a project with a number of walls that varies between 2 and 11 walls and there are 6 masons available. There are precedence relations between the walls. The solution process for the set of 9 instances with walls that are built with 2-mason crews took 131 seconds (in average), while the solution for the set of 9 instances with walls with 3-mason crews took about 14.3 minutes (in average). Based on the time to run the instances for each set, a linear regression was determined for the two sets. The regressions allow the decision maker to estimate the times h_{2t} and h_{3t}, measured in sec, that it will take (in average) to solve a problem with a number of walls given by w. The linear regression for the first set of instances (2-mason crews) is given by $h_{2t} = e^{-1.019}e^{0.771w}$, while the linear regression for the second set of instances (3-mason crews) is given by: $h_{3t} = e^{-0.60}e^{0.899w}$. The coefficient of determination R^2 for the first set is 0.975 and for the second set is 0.973.

Given the features of the model, each instance can be run independently (and in parallel) decomposing the problem in different sub-problems.

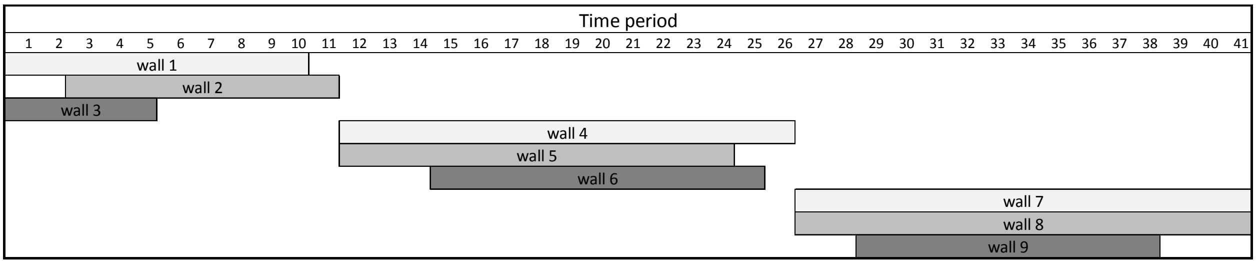

Figure 8 Schedule for the walls (changing availability of masons)

By dividing the problem in sub-problems, precedence relations can be easily considered (after solving each problem) and the completion time of the project is the sum of the completion times of the latest wall in each sub-problem. For example, the superintendent could have a project with 100 walls divided in 10 sub-problems, (there is a precedence relation between the sub-problems similar to the one in the case study). In this case, the solution set for the 100 walls takes 45 minutes (in average) using one personal computer. The time can be reduced to only 15 minutes if for instance three personal computers are used. One of the limitations is that when the number of walls (in each sub-problem) exceeds 12 walls, the computational time exceeds 3 hours, making it necessary to further divide the problem in sub-problems. The experiments in this section were performed on a Hewlett-Packard personal computer with 16 GB of RAM, Intel Core i7 running at 1.729 GHz (with 2 cores), on a 64-bit Microsoft Windows 7 Enterprise Edition operating system. The algorithm was implemented in Mosel version 3.2.2 and the mixed-integer optimization models were solved using Xpress-MP Optimizer version 22.01.04.

5.5 Addressing computational complexity

Typically, the choice of a heuristic or metaheuristic procedure such as genetic algorithms, dynamic programming, and particle swarm optimization follows the failure in using an exact programming model or when the problem features complicate the problem enough (i.e., considerably large number of integer variables or if the problem is NP-hard). Heuristic and metaheuristic procedures typically provide a faster solution in terms of computational time, but do not guarantee optimality. Furthermore, these heuristics often combine multiple candidate solutions to find near optimal solutions or a better solution (Ponz et al, 2017), but the combination process does not guarantee that the new solution will be improved. Therefore, the model was formulated using a mixed integer programming (MIP) approach (using linear constraints and a linear objective function) because this approach can 1) guarantee optimality (provides an exact solution) and 2) can be used to find improved solutions. By formulating the model as a MIP, the problem could be solved using commercial optimization software (given that the problem scale is not too large) and it can offer a benchmark for

future heuristic solution algorithms (Yin et al, 2017). Additionally, one of the benefits for developing a relatively simple model is that the method may have the potential to be used by superintendents for real allocation processes while allowing the user to easily incorporate and relax constraints. Given its simplicity, the model can also be used as a training tool for new superintendents and masons that have a relatively small knowledge on management principles and are starting to plan labor in jobsites. The MIP model proposed in this study can be decomposed into small sub-problems that can be solved independently (and in parallel) similar to the approach used in Jenna and Poggi (2013). This decomposition allows the user optimize the allocation of the crews while taking advantage of the MIP approach and minimizing the solving time.

The model developed was verified by comparing the results of the case study with that of the solution given by the model. The similarity of the results shows that the system accurately reflects the conditions on site and can be used to determine crew allocation strategies in masonry sites. Additionally, the optimum solution obtained was confirmed (and shared) with the owner and the project superintendent who was involved in the actual allocation on site. Also note that based on computer simulated instances, the optimum solution computational time is similar to other methods published (Yi and Lu, 2016), validating the developed formulation. Hopefully, the author will find economic resources to gather information of a larger number of real-case studies to further test the model.

6 CONCLUSIONS

The crew allocation process in masonry construction is challenging. Masonry is labor-intensive and often the superintendent needs to schedule and allocate crews to avoid disruptions and maximize production. Multiple masons with different skills, capabilities, and personalities are present in the jobsite at any one time and the superintendent needs to consider the characteristics of the masons to balance between the complexity of the job, the quality of work and the need for high production rates.

The proposed system aims to help contractors and superintendents allocate crews of workers in masonry projects. The model integrates a qualitative approach and a modeling approach in an attempt to incorporate masonry site realities and develop a system that can help alleviate some of the challenges faced by masonry contractors and superintendents in their day-to-day practices. The system solves the crew allocation problem by determining the optimal crew formation that minimizes time while considering labor requirements, availability of crews and precedence relations between the walls. Data from a real case study is used to compare the schedule and allocation performed on site with the one proposed by the model. The results show that the model can optimize the allocation of crews to reduce the completion time to build the walls by selecting the proper mason for the proper wall. One assumption for the system is that the three factors that affect productivity (compatibility, suitability, and craft) influence the productivity equally. It was natural to propose that assumption since there was no further information about the factors and to what extent they influence the productivity. Note that the case study was developed in a site of moderate size thus these assumptions may change given a different size project. The novelty of the presented system is that it includes realistic and masonry site-specific characteristics and it sets the basis for developing a more specialized tool for allocating crews of workers in the masonry industry. By incorporating workers attributes and site conditions, this tool assigns the proper worker to the proper task.

Next steps for future research can include considerations that may happen on masonry sites. For instance, in some cases crews may interrupt work on a wall when another trade has to work on the wall or the crew needs to build scaffold. Interruptions can be included by relaxing equations (7) and (8) to account for additional time to complete a wall. Similarly, the assumption of having fixed resources can be easily relaxed in equation (9), leading to a more flexible model that handles (automatically) the addition of resources at some expense by considering the marginal cost of adding labor and the additional amount of labor that is needed at any given time. Additionally, future studies can be conducted to determine the coefficient for each one of the factors that affects productivity as well as a function that can precisely measure soft factors. Further analysis of compatibility and personnel well-being requires additional research. Future work will probably lead to insights in measuring and quantifying how workers get along in order to assemble teams that are more effective.

ACKNOWLEDGMENTS

The author thanks Dr. Jean C. Cortissoz for his valuable comments on the mathematical formulation and interpretation during her visit at Universidad de los Andes in May 2017. The author would also like to thank Dr. Andres L. Medaglia for useful suggestions on the model and Dr. Daniel Castro-Lacouture for his encouragement.

REFERENCES

Adeli, H. and Karim, A. (1997). Scheduling/Cost Optimization and Neural Dynamics Model for Construction. *J. Constr. Eng. Manag*, **123**(4), 450-458.

Adeli, H., and Kumar (1995). Distributed genetic algorithm for structural optimization. *Journal of Aerospace Engineering*, **8**(3), 156-163.

Ahmadian Fard Fini, A., Rashidi, T., Akbarnezhad, A., and Travis-Waller, S. (2015). Incorporating Multiskilling and Learning in the Optimization of Crew Composition. *J. Constr. Eng. Manag*, **142**(5), 401-409.

Al-Bazi, A., and Dawood, N. (2010). Developing Crew Allocation System for the Precast Industry Using Genetic Algorithms. *Comput Aided Civ Infrastruct. Eng*, **25**(8), 581-595.

Al-Bazi, A., and Dawood, N. (2017). Simulation-based optimisation using simulated annealing for crew allocation in the precast industry, *Architectural Engineering and Design Management*, 10 (1), 1-18.

Alfares, H. K. (2004). Survey, categorization, and comparison of recent tour scheduling literature. *Annals of Operations Research*, **127**(1), 145–175.

Arditi, D. and Bentotage, S. N. (1996), System for Scheduling Highway Construction Projects. *Comput Aided Civ Infrastruct. Eng*, **11**(1), 123–139.

Arditi, D., Tokdemir, O.B., Suh, K. (2001). Effect of learning on line-of balance scheduling. *International Journal of Project Management*, **19**(5), 265-277.

Batta, R., Berman, O., and Wang, Q. (2007). Balancing staffing and switching costs in service center with flexible servers. *Eur. J. Oper Res*, **177**(2), 924–938.

Bellenguez-Morineau, O., and Neron, E. (2007). A Branch-and-Bound method for solving Multi-Skill Project Scheduling Problem, *Operations Research*, **41**(2), 155-170.

Bhoyar, S., and Parbat, D. K. (2014). Optimal scheduling for repetitive construction projects with multiple resource crews. International Journal of Emerging Technology and Advanced Engineering, 4(6), 302–307.

Biruk, S., and Jaśkowski, P. (2008). Simulation modelling construction project with repetitive tasks using petri nets theory. Journal of Business Economics and Management, 9(3), 219–226.

Brucker, P., Qu, R., and Burke, E. (2011). Personnel scheduling: Models and complexity. *Eur. J. Oper Res*,

210(3), 467-473.

Brunner, J.O., Bard, J. F., and Kolisch, R. (2011). Midterm scheduling of physicians with flexible shifts using branch and price. *IIE Transactions*, **43**(2), 84–109.

Cai, X., and Li, K. N. (2000). A genetic algorithm for scheduling staff ofmixed skills under a multi-criteria. *Eur. J. Oper Res*, **125**(2), 359–369.

Caprara, A., Toth, P., Vigo, D., and Fischetti, M. (1998). Modeling and solving the crew rostering problem. *Operations Research*, **46**(6), 820-830.

Chen, P.H., and Shahandashti, S.M. (2009). Hybrid of genetic algorithm and simulated annealing for multiple project scheduling with multiple resource constraints. *Autom. Constr*, **18**(4), 434-443.

Chu, S.C.K. (2007). Generating, scheduling and rostering of shift crew-duties: applications at the Hong Kong International Airport, *Eur. J. Oper Res,* **177**(2), 1764–1778.

Corominas, A., Lusa, A.,and Olivella, J. (2012). A detailed workforce planning model including non-linear dependence of capacity on the size of the staff and cash management. *Eur. J. Oper Res*, **216**(2), 445–458.

Corominas, A., Pastor, R., and Plans, J. (2008). Balancing assembly line with skilled and unskilled workers. *Omega*, **36**(6), 1126–1132.

Damci, A., Arditi, D., and Polat, G. (2013). Multiresource Leveling in Line-of-Balance Scheduling. *J. Constr. Eng. Manag*, **139**(9), 1108-1116.

De Bruecker, P., Van den Bergh, J., Beliën, J., and Demeulemeester, E. (2015). Workforce planning incorporating skills: State of the art. *Eur. J. Oper Res*, **243**(1), 1-16.

de Matta, R., and Peters, E. (2009). Developing work schedules for an inter-city transit system with multiple driver types and fleet types. *Eur. J. Oper Res*, **192**(3), 852–865.

Debels, D., De Reyck, B., Leus, R., and Vanhoucke, M. (2006). A hybrid scatter search/electromagnetism meta-heuristic for project scheduling. *Eur. J. Oper Res*, **169**(2), 638-653.

Dück, V., Ionescu, L., Kliewer, N., and Suhl, L. (2012). Increasing stability of crew and aircraft schedules, *Transportation Research*, **20**, 47-61.

Elazouni A.M. and Gab-Allah., A.A. (2004). Finance-based scheduling of construction projects using integer programming. *J. Constr. Eng. Manag*, **130**(1), 15–24.

El-Gafy, M. A. (2006). Resource allocation in repetitive construction schedules using ant colony optimization, pp. 515–523. Retrieved June 4, 2017, from http://www.irbnet.de/daten/iconda/CIB4427.pdf

El-Rayes K., and Moselhi, O. (2001). Optimizing resource utilization for repetitive construction projects. *J. Constr. Eng. Manag*, **127**(1), 18-27.

Erdogan, G., Erkut, E., Ingolfsson, A., and Laporte, G. (2010). Scheduling ambulance crews for maximum coverage, *Journal of the Operational Research Society* **61**, 543–550.

Faghihi, V., Nejat, A., Reinschmidt, K.F, and Kang, J.H. (2015). Automation in construction scheduling: a review of the literature. *Int J Adv Manuf Technol*, **81** (9): 1845-1856.

Florez L, Castro-Lacouture D, and Medaglia A L. (2013). Sustainable workforce scheduling in construction program management. *Journal of the Operational Research Society*, **64**(8), 1169-1181

Florez, L. (2015). Decision support system for masonry labor planning and allocation considering productivity and social sustainability. Ph. D. Dissertation, Georgia Institute of Technology, Atlanta Georgia.

Francis Siu, M.F., Lu, M., Abourizk, S. (2015). Methodology for Crew-Job Allocation Optimization in Project and Workface Scheduling. Proceedings of the Computing in Civil Engineering Conference, 652-659.

Gao, L., Xie, C., Zhang, Z. and Waller, S.T. (2012). Network-Level Road Pavement Maintenance and Rehabilitation Scheduling for Optimal Performance Improvement and Budget Utilization. *Comput Aided Civ Infrastruct. Eng*, **27**(4), 276-287.

Gomar, J.E., Haas, C.T., and Morton, D.P. (2002). Assignment and allocation optimization of partially multiskilled workforce. J. Constr. Eng. Manag, **128**(2), 103-109.

Haas, C.T., Rodriguez, A.M., Glover, R., and Goodrum, P. (2001). Implementing a Multiskilled Workforce. *Journal of Construction Management and Economics*, **19**(6), 633-641.

Hassanein, A., and Melin, J. (1997). Crew design methodology for construction contractors. *J. Constr. Eng. Manag and Management*, **123**(3), 203-207.

Hegazy, T., and Kamarah, E. (2008). Efficient repetitive scheduling for high-rise construction. *J. Constr. Eng. Manag*, **134**(4), 253-264.

Hegazy, T., and Wassef, N. (2001). Cost optimization in projects with repetitive nonserial activities. *J. Constr. Eng. Manag*, **127**(3), 183-191.

Horn, M., Jiang, H., Kilby, P. (2007). Scheduling patrol boats and crews for the Royal Australian Navy, *Journal of the Operational Research Society*, **58**(2), 1284-1293.

Ioannou, P. and Yang, I. (2016). Repetitive Scheduling Method: Requirements, Modeling, and Implementation. *J. Constr. Eng. Manag*, **142**(5), 230-262.

Ipsilandis, P.G. (2007). Multiobjective linear programming model for scheduling linear repetitive projects. *J. Constr. Eng. Manag* 133(6), 417–424.

Karim, A. and Adeli, H. (1999a). Object-Oriented Information Model for Construction Project Management, *J. Constr. Eng. Manag*, **125**(5), 361-367.

Karim, A. and Adeli, H. (1999b). CONSCOM: An OO Construction Scheduling and Change Management System. *J. Constr. Eng. Manag*, **125**(5), 368-376.

Klanšek,U. (2015). Mixed-Integer Nonlinear Programming Model for Nonlinear Discrete Optimization of Project Schedules under Restricted Costs. *J. Constr. Eng. Manag*, **142**(3), 733-747.

Koo, C., Hong, T., Yoon, J., and Jeong, K. (2016). Zoning-based Vertical Transportation Optimization for Workers at Peak Time in a Skyscraper Construction. *Comput Aided Civ Infrastruct. Eng*, **31**(11), 826-845.

Kumar, A., Dijkman, R., and Song, M. (2013). Optimal resource assignment in workflows for maximizing cooperation. Business Process Management. *Lecture Notes in Computer Science*, (8094), 235-250.

Lagodimos, A.G., and Leopoulos, V. (2000). Greedy heuristic algorithms for manpower shift planning. *Intl Journal of Production Economics*, **68**(1), 95–106.

Lee, D.-E., Lim, T.-K. and Arditi, D. (2011). An Expert System for Auditing Quality Management Systems in Construction. *Comput Aided Civ Infrastruct. Eng*, **26**(8), 612-631.

Li, N., and Li, L. X. (2000). Modeling staffing flexibility: A case of China. *Eur. J. Oper Res*, **124**(2), 255–266.

Lim, T.K., Yi, C.Y., Lee, D.E., and Arditi, D. (2014), Concurrent Construction Scheduling Simulation Algorithm. *Comput Aided Civ Infrastruct. Eng*, **29**(6), 449-463.

Lin, H.T., Chen, Y.T., Chou, T.Y., and Liao, Y.C. (2012). Crew rostering with multiple goals: An empirical study. *Computers and Industrial Engineering*, **63**(2), 483-493.

Lin, K.L. (2011). Human Resource Allocation for Remote Construction Projects. *J. Constr. Eng. Manag*, **27**(1), 13-20.

Liu, S.S. and Wang, C.J. (2010). Profit optimization for multiproject scheduling problems considering cash flow. *J. Constr. Eng. Manag*, **136**(12), 1268–1278.

Lu, M., Lam, H.C., and Tang S.L. (2008). Skilled laborer management in handling concurrent building projects at multiple sites: the bar benders job scheduling problem. *Intl Conf. on Constr in Developing Countries*, Aug 4-5, Pakistan.

Lucko, G. (2011). Integrating Efficient Resource Optimization and Linear Schedule Analysis with Singularity Functions. *J. Constr. Eng. Manag*, **244**(2), 45-55.

Maravas, A., Pantouvakis, J.P. (2011). A Fuzzy Repetitive Scheduling Method for Projects with Repeating Activities, *J. Constr. Eng. Manag*, **137**(7), 561–564.

Marzouk, M., El-Dein, H.Z., and El-Said., M. (2007). Application of Computer Simulation to Construction of Incrementally Launching Bridges. *J. Constr. Eng. Manag*, **13**(1), 27-36.

Maxwell, D. A., Back, W. E., and Toon, J. (1998). Optimization of crew configurations using activity-based costing. *J. Constr. Eng. Manag*, **124**(2), 162-168.

Morton, D.P. Popova, E. (2004). A Bayesian stochastic programming approach to an employee scheduling problem, *IIE Transactions*, **36**(1), 155–167.

Moselhi, O and Alshibani, A (2007). Crew optimization in planning and control of earthmoving operations using spatial technologies. Itcon, 12 (2), 121-137.

Nassar, K (2005). Evolutionary optimization of resource allocation in repetitive construction schedules, ITcon, **10**(1), 265-273.

Nassar, K. (2005). Evolutionary optimisation of resource allocation in repetitive construction schedules. ITcon, 10, 265–273.

Nussbaum, M., Singer, M., Rosas, R., Castillo, M., Flies, E., Lara, R., and Sommers, R. (1999). Decision support system for conflict diagnosis in personnel selection. *Information & Management*, **36**(1), 55-62.

Palaneeswaran, E. and Kumaraswamy, M. (2000). Contractor selection for design/build projects. *J. Constr. Eng. Manag*, **126**(5), 331-339.

Ponz-Tienda, J. L., Pellicer, E., Benlloch-Marco, J and Andres-Romano, C. (2015). The Fuzzy Project Scheduling Problem with Minimal Generalized Precedence Relations, *Comput Aided Civ Infrastruct. Eng*, **30**(11), 872-891.

RSMeans (2017). RSMeans Reed construction data. Last accessed from http://rsmeans.reedconstructiondata.com/ on May 31, 2017.

Senouci, A., and Al-Derham H.R. (2008). Genetic algorithm-based multi-objective model for scheduling of linear construction projects. *Adv Eng Software*, **39**(12), 1023–1028.

Shahhosseini, V., and Sebt, M. H. (2011). Competency-based selection and assignment of human resources to construction projects. *Scientia Iranica*, **18**(2), 163-180.

Srour, I. M., Haas, C. T., and Morton, D. P. (2006). Linear Programming Approach to Optimize Strategic Investment in the Construction Workforce. *J. Constr. Eng. Manag*, **132**(11), 1158-1166.

Süer, G. A., and Tummaluri, R. R. (2008). Multi-period operator assignment considering skills, learning and forgetting in labour-intensive cells. *International Journal of Production Research*, **46**(2), 469-493.

Thiel, M.P. (2008). Team-oriented airline crew rostering for cockpit personnel, *Computer-Aided Systems in Public Transport*, **6**(1), 91–114.

Tiwari, V., Patterson, J. H., and Mabert, V. A. (2009). Scheduling projects with heterogeneous resources to meet time and quality objectives. *Eur. J. Oper Res*, **193**(3), 780–790.

Van den Bergh, J., Beliën, J., De Bruecker, P., Demeulemeester, E., and De Boeck, L. (2013). Personnel scheduling: A literature review. *Eur. J. Oper Res*, **226**(3), 367-385.

Wongwai, N., and Malaikrisanachalee, S. (2011). Augmented heuristic algorithm for multi-skilled resource scheduling. *Autom. Constr.*, **20**(4), 429–445.

Yi,W., and Chan, A. (2014). Optimal Work Pattern for Construction Workers in Hot Weather: A Case Study in Hong Kong. *Journal of Computing in Civil Engineering*, **29**(5), 419-425.

Yi, C, and Lu, M. (2016). A mixed integer linear programming approach for temporary haul road design in rough-grading projects. *Autom. Constr*, **71**(4), 314-324.

Yunes, T.H., Moura, A.V. de Souza, C.C. (2005). Hybrid column generation approaches for urban transit crew management problems, *Transportation Science*, **39**(3), 273–

288
Zhou, J., Love, P., Wang, X., Teo, K., and Irani, Z. (2013). A review of methods and algorithms for optimizing construction scheduling. *Journal of the Operational Research Society*, **174**(3), 1091-1105.