Optimal Crew Design for Masonry Construction Projects Considering Contractor’s Requirements and Workers’ Needs

Laura FLOREZ1 and Daniel CASTRO-LACOUTURE2

1 Ph.D. Candidate, School of Building Construction, Georgia Institute of Technology, 280 Ferst Drive, 1st Floor, Atlanta, GA 30332; PH (404) 385-6964; FAX (404) 894-1641; email: lflorez3@gatech.edu

2 Associate Professor, School of Building Construction, Georgia Institute of Technology, 280 Ferst Drive, 1st Floor, Atlanta, GA 30332; PH (404) 385-6964; FAX (404) 894-1641; email: dcastro@gatech.edu

ABSTRACT

Masonry construction is labor-intensive. Its operations involve little to no mechanization and require a large number of crews made up of workers with diverse skills. Relationships between crews are tight and very dependent. Often tasks have to be completed concurrently and crews have to share resources and work space to complete their work. One of the problems masonry contractors face is the need to design crews, that is, determine the number of crews and the composition of each crew to be effectively used in the construction process to maximize workflow. This study proposes a mixed integer optimization model to assist contractors in the allocation of crews in masonry projects. To address realistic scenarios experienced by the contractors on masonry construction job sites, the model incorporates the rules that contractors use for crew design and makeup as well as time constraints. In addition, the model considers workers’ needs such as labor stability. The proposed model can be a valuable tool to assist masonry stakeholders in the process of allocating crews while meeting contractor’s requirements and workers’ needs.

INTRODUCTION

Human resource allocation in construction is the process of assigning crews of workers to tasks (Al-Bazi and Dawood 2010). Tasks may require several crews with diverse skills to be completed and crews need to be scheduled to ensure an efficient output and adequate control (Hassanein and Melin 1997). This allocation process in masonry construction is challenging. Masonry is labor-intensive and often times crews have to work concurrently and share work space to complete their work. A key characteristic of masonry projects is that work is divided in different wall sections, depending on which area is available and accessible for crews to work in. Often times, crews complete their work on a section, but then have to come back later to complete the other part of the work. Due to this characteristic, every time a wall section or part of a wall section is completed, the labor configuration is reorganized. This results in temporary crews that need to be constantly moving. One of the problems masonry contractors face is the need to allocate crews to maximize workflow while satisfying contractors’ constraints and worker’s needs.
There are several approaches that have been developed to allocate human resources in construction. Al-Bazi and Dawood (2010) presented a strategy to allocate crews of workers in the precast concrete industry using genetic algorithms-based simulation modeling. Lin (2011) proposed a decision-making model for human resource allocation in remote construction projects. El-Rayes and Moselhi (2001) developed an optimization model that uses dynamic programming for repetitive construction projects. Maxwell et al. (1998) presented a stochastic simulation program to measure the elapsed time and activity cost of each candidate crew. Their proposal uses an optimization rule to determine the best crew configuration. Cheng et al. (2006) developed a team-based resource planning method for labor power by combining business process reengineering and a simulation approach. Jun and El-Rayes (2010) proposed an optimization model to schedule multiple labor shifts in construction projects. A review of the aspects and modeling approaches in personnel allocation and scheduling can be found in Brucker et al. (2011).

However, there is no method to optimally allocate crews of workers in masonry construction projects that considers simultaneously both contractor’s requirements and workers’ needs. The employment of brick and block masons is projected to grow 40% and that of mason helpers 60% from 2010 to 2020 ([Bureau of Labor Statistics] (BLS) 2013) and their work will continue to be increasingly important in schools, hospitals, and apartment buildings. Therefore, close attention should be paid to the planning and estimating process of masonry work to increase efficiency and project performance.

MASONRY CONSTRUCTION

Masonry activities such as scaffold installation, mixing mortar, laying block, cutting block, and grouting are labor dependent and require a large number of workers with diverse skills. Work is physically demanding (Spielholz et al. 2006) and masons as well as mason helpers (laborers) often lift heavy materials and stand for long periods of time (Boschman et al. 2011). A number of studies have identified masonry features that may impact masonry crew’s performance. These include excessive block cutting, numerous corners (Sanders and Thomas 1991), numerous openings (Hassanein and Melin 1997), the use of non-adjustable scaffolds, and the size of masonry units (Mortlock and Whitehead 1970). Additionally, masons work outdoors and are subject to poor weather conditions that reduce their work activity (BLS 2013).

Masonry contractors divide work in different wall sections and usually work with crews (Ng and Tang 2010) to accomplish a specific task. Tasks are dictated by what area of the building is accessible and available for crews to work in, and what pipes are already in place or what openings are marked and ready so that masons can work around. When a wall section is completed, often times, crews are re-assembled and the contractor is responsible of configuring and assigning crews with different skills (Ng and Tang 2010) to produce good quality works by means of capitalizing skills. Due to this task division, multiple crews are present on the jobsite at any one time. Even though crews work independently within the range of their own skills, contractors need to properly sequence their work to complete tasks and maximize
workflow. Therefore, to optimally allocate workers, contractors need to consider not only their requirements but also the workers’ needs.

**Contractor’s requirements**

Contractors follow a process to design and configure crews. The process is applied by considering a set of rules that impact the whole crew design and ultimately helps contractors determine the number of workers per crew and the composition of each crew (Hassanein and Melin 1997). To determine the rules that contractors use to design and makeup crews, this study used a contextualist research approach (Green et al. 2010) to gather knowledge and information in a masonry project about the context and implicit practices that can only be collected in the field (Pink et al. 2010). The project was a multistory building of mixed-use space with a parking structure. Quasi-ethnographic observations were conducted to understand masonry work practices, task distributions, workers’ roles, and ultimately identify the rules a masonry contractor uses to configure crews. The rules presented in this study were determined from the extensive observations conducted in the project and are coupled with the rules identified in Hassanein and Melin (1997).

**Rule 1: Crew composition**

In general contractors don’t have a typical crew, but they have some guidelines as to the worker’s ratio in a crew that they use and try to maintain. This ratio dictates the typical number of laborers per number of masons that is used when forming crews (Hassanein and Melin 1997).

**Rule 2: Crew operators**

There are some basic operators that need to be present in the jobsite. There always has to be a laborer in the saw, a laborer mixing the mortar, and a laborer operating the forklift. This last one increases with the number of crews present in the jobsite.

**Rule 3: Crew size**

In regards to the crew size, there is a maximum number of workers that are assigned to a non-working foreman. Typically foremen determine the maximum number of workers that they can handle to guarantee an adequate control (Hassanein and Melin 1997).

**Rule 4: Crew control**

The foreman has a working assistant foreman that monitors crews and helps layout the job. The number of assistant foremen is dictated by the foreman and depends on the number of crews. Usually the number of crews is divided equally among the assistant foremen.

**Rule 5: Learning curve**

When forming crews, the foreman (or assistant foreman) tends to keep the same masons in a crew due to the learning curve. Masons that have worked together know what they are doing and have identified ways to collaborate.
Rule 6: Compatibility of labor
The foreman (or assistant foreman) considers a compatibility factor, that is, how masons get along to keep production up. Masons have different ways to work and get things done. Some masons work well together, but some do not get along or the way they work is not compatible. The foreman (or assistant foreman) tries to form crews with workers that are compatible because masons that work well together are more efficient and this can improve quality and increase throughput (Kumar et al 2013).

Rule 7: Quality of work
When the quality of work is a factor, experienced masons (i.e., journeymen) are assigned to wall sections that require a high demand of craftwork (e.g., openings, corners, details), whether non-experienced masons (i.e., apprentices) are assigned to non-craft work (e.g., straight walls). The foreman, or assistant foreman, knows which worker is good at what, based on the skills.

Workers’ needs
Workers place a great value on requirements such as involvement, respect, and sense of personal growth (Lingard and Sublet 2002). From the contractor’s point of view, a project that offers continual employment allows the contractor to maintain an acceptable skill level and helps generate a sense of commitment to the job from the workers (MacKenzie et al. 2010). In addition, it decreases the possibility of schedule overruns and leads to less deviations from the normal workflow (Lee et al. 2004). From the worker’s point of view, a job that gives stable work increases employment duration and provides opportunities for career growth (Loosemore et al. 2003). Furthermore, a change often implies not only a change in pay grade, but also the need to get familiar with new workers and practices. That is, workers prefer jobs that will keep them busy all the time. This situation increases labor skill level. Workers prefer to work with skilled peers because they are good at what they do. This decreases the possibility of rework and helps keep a normal workflow.

The proposed way to increase employment duration is based on the labor stability indicator developed in Florez et al. (2013). By considering labor stability, a construction project smooths the allocation of workers to avoid drastic measures and minimize the variation of the number of workers. Therefore, a stable workforce provides benefits to the workers in terms of employment duration (Florez et al. 2013) and benefits to the contractor in terms of workflow (Lee et al. 2004).

OPTIMIZATION MODEL FOR CREW DESIGN AND ALLOCATION IN MASONRY CONSTRUCTION
The model considers a masonry project, e.g., high school, university research building, hospital. The project is divided into different tasks that require labor resources. Associated with each worker, there is a subset of skills for which the worker is qualified such as foreman, assistant foreman, journeymen mason, apprentice mason, laborer, machine operator, and saw operator. A project demands crews made up of workers with different skills that can be used flexibly across any task in a project, as long as they are qualified for that task.
The project is built using labor resources with different skills. The owner sets a date of completion of the project and with this date and considering technical requirements, the contractor has to design and allocate crews to complete the project on schedule. In this case, the model will allocate workers in order to satisfy the rules that contractors use for the design and makeup of crews. In addition, the model will implement thoughtful workforce strategies, that is, employees that are assigned to work on the project may expect longer employment duration and continuity in work assignments.

Figure 1 shows the optimization framework that supports the masonry contractor in the process of designing crews and allocating crews of workers in masonry construction projects.

![Optimization model framework](image)

The data input module collects the information on the parameters required by the project. These parameters were determined based on the semi-ethnographic observations and conversations conducted in the masonry construction jobsite. The knowledge gathered in the jobsite is used to incorporate masonry realities to the model and better reflect what is happening in the field. From the field, the rules that contractors use to design and makeup crews were determined such as requirements in terms of the maximum number of crews that can be working concurrently at one point in time and constraints such as the maximum number of crews per non-working assistant foreman. Please see the sub-section “Contractor’s requirements” for a detailed explanation of the rules.

The data input module also includes for every time period, information on the availability of workers. Table 1 shows the labor requirements demanded by four wall sections per time period. Note that some wall sections may not require certain resources and the demand for a resource may vary between time periods.
Table 1. Resource Requirements

<table>
<thead>
<tr>
<th>Wall section 1</th>
<th>Time period</th>
<th>Wall section 2</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journeyman mason</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Apprentice mason</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Laborer</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall section 3</th>
<th>Time period</th>
<th>Wall section 4</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apprentice mason</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Laborer</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 shows the labor availability over the planning horizon. This supply has variations, reflecting changing availability of workers due to vacation. As a result, resource capacities varying with time may cause that all wall sections cannot be started at the same time or that some crews may need to be reorganized because a worker may not longer be available. The data input also includes the time parameters, which define the planning horizon for constructing the project and the precedence relations between wall sections.

Table 2. Labor Availability

<table>
<thead>
<tr>
<th>Workers</th>
<th>Time interval of resource availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worker 1</td>
<td>(Jan 2014, Oct 2014)</td>
</tr>
<tr>
<td>Worker 2</td>
<td>(Mar 2014, Jun 2014)</td>
</tr>
<tr>
<td>Worker 3</td>
<td>(Aug 2014, Dec 2014)</td>
</tr>
<tr>
<td>Worker 4</td>
<td>(Apr 2014, Dec 2014)</td>
</tr>
<tr>
<td>Worker 5</td>
<td>(Sep 2014, Dec 2014)</td>
</tr>
</tbody>
</table>

Table 3 shows the compatibility between workers. Assume that the foreman (or assistant foreman) knows the way each mason works and how well masons work together. That is, the compatibility factor accounts for the how well and efficient masons work together.

Table 3. Compatibility Factor between Workers

<table>
<thead>
<tr>
<th>Worker 1</th>
<th>Worker 2</th>
<th>Worker 3</th>
<th>Worker 4</th>
<th>Worker 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worker 1</td>
<td>-</td>
<td>0.80</td>
<td>0.40</td>
<td>0.50</td>
</tr>
<tr>
<td>Worker 2</td>
<td>0.80</td>
<td>-</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Worker 3</td>
<td>0.40</td>
<td>0.50</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td>Worker 4</td>
<td>0.50</td>
<td>1.00</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Worker 5</td>
<td>0.10</td>
<td>0.80</td>
<td>0.90</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Masons that work well together will have a compatibility factor of 1, whereas masons that do not work well together will have a compatibility factor of 0. For instance, if worker 2 and worker 4 are assigned to the same crew they can work...
together efficiently (compatibility factor 1.00). On the other side if worker 5 and worker 1 are assigned to the same crew, the production may come down (compatibility factor 0.10).

Table 4 shows the skills for each worker. The binary parameter takes the value of 1 if a worker has that skill; it takes the value of 0, otherwise. Note that some workers have different skills that will allow them to work in activities that require those skills. For instance, a mason at the journeyman level can be allocated to a wall that requires craft work and to a wall that only requires apprentice level. That is, worker 1 is a journeyman, and can be allocated to either a wall that requires craft work (journeyman) or to a straight wall with no openings (apprentice). Moreover, worker 1 also has skills to be a laborer. Therefore, worker 1 could be allocated as a laborer to help a mason or to operate the saw or the fork lift. Additionally, some skills may require special permits such as the fork lift operator that needs a license to operate machines.

Table 4. Labor Skills

<table>
<thead>
<tr>
<th></th>
<th>Foreman</th>
<th>Journeyman</th>
<th>Apprentice</th>
<th>Laborer</th>
<th>Saw operator</th>
<th>Fork lift operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worker 1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Worker 2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Worker 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Worker 4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Worker 5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Once all the data input is entered, the optimization module builds the model that considers workflow when allocating labor to the project. The allocation process consists of assigning the time needed to be working in a specific task to each of the workers in the crew. Each task demands a certain number of crews and each crew demands a certain number of workers with different skills. To build the schedule, the model uses binary decision variables to define the times each worker is working in a specific task. The model determines the total number of crews and ultimately the total number of workers that are working along the planning horizon. Furthermore, the model determines which worker should be working in which crew and doing which task.

The model’s objective is to allocate crews of workers so that the workflow, that is, production in terms of number of masonry units is maximized. The reporting module of the optimization model is a detailed schedule of the times to start tasks, the number of workers and the skills of the workers needed as well as the crew configuration under the optimal schedule.

DISCUSSION

The crew allocation process in masonry construction is challenging. Masonry is labor-intensive and often crews have to sequence their work to avoid disruptions and maximize production. Multiple crews with different skills are present on the jobsite at any one time and it is difficult to determine when each crew should be
working and the workers that need to be assigned to a crew. Consequently, contractors need tools to allocate crews to eliminate time delays.

The proposed optimization model aims to help contractors allocate crews of workers in masonry projects. The model integrates a contextualist research approach and a modeling approach in an attempt to understand the challenges in masonry construction jobsites and develop a tool that can help alleviate some of the issues faced by masonry decision-makers in their day-to-day practices. Typical contractors’ requirements are included to address realistic scenarios experienced by masonry contractors in the jobsite. These requirements dictate the rules contractors use to design and makeup crews based on experience. In addition, the model considers workers’ needs such as labor stability that helps workers stay longer on the project and increase continuity of job assignments. With the model, contractors are able not only to determine the optimal starting times for each of the crews, but also to quantify the number of crews and ultimately the number of workers needed to build a masonry project.

These new considerations should prove useful to masonry contractors and enable them to optimize the allocation of multiple workers in order to maximize workflow. An optimal schedule that considers the needs of workers and contractors contributes to formulate strategies to make project management more sustainable and increase the benefits achieved by both workers and contractors. As further developments, the model may be modified to solve more complicated crew allocation problems by considering processes with other factors. Factors such as the impact of different working shifts or space availability can be considered in detail while developing the allocation system.

ACKNOWLEDGMENTS
The authors greatly appreciate all the managers, block masons, laborers, and field personnel of the contractor firm for sharing information and participating in the research process.

REFERENCES


