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Defining a Mathematical Function for Labor Productivity in Masonry Construction: A Case Study

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Abstract

Labor productivity has a profound impact on construction management. The accurate prediction of productivity is essential to effectively plan operations that depend on time and cost and is critical for the success of a construction project for both the contractor and the owner. However, predicting productivity of operations is challenging due to the multiple characteristics of workers, the interrelationships between workers, and the site conditions that impact the performance of crews and affect project goals. This paper proposes a methodology to quantify the factors that affect productivity in masonry construction. We have considered three factors: compatibility, suitability, and craft. Standardized data-collection techniques are used to consolidate data from three masonry sites and mathematically define a productivity function that relates workers characteristics and crews with site conditions. The function, increasing in its arguments, determines the factors that most affect masonry productivity and the factor's effects. The most interesting part is to be able to identify the convexity properties of this function because its theoretical interpretation will have implications on the impact of the superintendent's decisions when forming crews. The proposed mathematical function can enable superintendents to better plan, schedule, and manage masonry crews.

Keywords: crew formation, labor management, masonry construction, productivity function

1. Introduction

Labor productivity is one of the key factors affecting the overall performance of a construction project [1]. Labor costs usually account for about 30-50% of the total project costs [2] and labor is considered the strategic resource in any project for ensuring improved productivity and industry competitiveness [3, 4]. By effectively managing labor, the productivity of all the other inputs can be simultaneously enhanced and all of the benefits available through improved productivity can be realized. Crew formation is one of the key tasks in labor management [5]. The process of selecting the workers in a crew and assigning crews to different tasks is crucial for ensuring the success of a construction project and improved labor productivity. Florez [6] conducted a review to understand the functioning of masonry crews and determine the factors that impact the productivity of crews. Through extensive site observations and interviews with masonry practitioners, it was found that typically the superintendent in the jobsite considers three factors (that impact productivity) when grouping workers in crews: compatibility, suitability, and craft. This paper aims to define a function that determines the three factor's effects on productivity. The function alongside its theoretical interpretation will provide a means for determining the extent of the superintendent's decisions and can become a powerful tool for the process of planning and managing masonry crews.

2. Masonry construction

Masonry construction is labor-intensive. Processes involve little to no mechanization and require a large number of crews made up of workers with diverse skills, capabilities, and personalities [7]. In masonry construction, management of labor is one of the key factors to balance production and quality [8]. Tasks may require several

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crews with diverse skills to be completed and crews need to be scheduled to ensure an efficient output and adequate control [4]. This allocation process in masonry construction is challenging. Every time a wall section or part of a wall section is completed, the labor configuration is reorganized [9]. This results in temporary crews that need to be constantly moving and the superintendent is responsible of re-organizing the crews to make sure the masons selected to build the walls have the required characteristics to produce good quality work within the given time constraints.

2.1. *Factors that impact crew formation*

Results from the exploratory study in [6] indicate there are different characteristics of masons that need to be considered because these have an impact on the quality of the work and the productivity of a crew. These criteria are used by masonry practitioners in forming crews and are used as guidelines when the superintendent is in the jobsite trying to group workers to form the most efficient crew. The three factors that impact productivity found in [6] are detailed below:

- Compatibility: masons have different personalities, ways to work, and get things done. Some masons work well together, but some masons just do not work well with certain other masons. They just do not get along and when they work with each other they seem to get less productive. The superintendent tries to form crews with workers that are compatible because grouping masons that work well together can increase throughput [10].
- Suitability: masons have different specialties and can be more suitable to work in a specific type of wall. Some masons are very good levelling and plumbing and therefore are efficient working on wall sections that require a high demand of technical work (e.g., openings, intricate corners, details, building leads, penetrations). Other masons are not good with the level and the plumb but are very efficient working in the line and in non-technical work (e.g. straight walls or walls with little to no openings). The superintendent tries to assign a mason to a wall that matches the specialty of the mason to the type of work required in the wall.
- Craft: masons learn (and know) how to lay brick and block but are usually faster at one craft than the other. Some masons are good at handling smaller units and are more detailed so they are better brick layers, whereas some masons are stronger and are better at laying block. In other words, in masonry there are bricklayers and there are block masons. The superintendent tries to assign a mason to a wall section where the material match the craft the mason is more efficient at.

3. Managing and scheduling labor in masonry

The proposed model is based on the mixed-integer program by Florez [6]. The model assigns crews to minimize the time to build walls in a masonry project. The allocation process consists of determining which crew is going to be working in which wall and at what time. Each wall demands a number of masons and each crew is comprised of a certain number of masons, so the model determines which crew from the crews available is assigned to each wall. To build the schedule, the model uses binary decision variables to define the times each crew is working in a specific wall. Note that the model only allows *go-no-go* decisions, that is, walls cannot be partially built and once they are in progress are not interrupted. The reporting module of the optimization model is a detailed schedule of the times to start the walls, the number of masons, and the crew configuration under the optimal schedule.

Mathematically, the model's objective is to minimize the total execution time to finish the walls. Aside from the structural binary variables y_{ijt} that determine if wall i is assigned to crew j and scheduled to start at the beginning of time t, the decision variable $C_{\max}$ represents the makespan of the project schedule. The latter variable allows us to define the proposed objective function:

$$\min = C_{\max} \tag{1}$$

where (1) minimizes the total execution time when scheduling all the walls. To accomplish this objective, it is important to include in the model the following constraints:

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

where v_{ij} is the time it takes crew j to finish wall i.The proposed model also defines the following set of auxiliary variables. Structural binary variables x_{ijt} denote if crew j is assigned to wall i at time t. In addition the (auxiliary) binary variables z_{ij} determine if wall i is assigned to crew j. Along with objective (1) the model also includes the following constraints:

$$\sum_{t=1}^{T}\sum_{j\in J_i} y_{i,j,t} = 1 \qquad , \; i \in I \tag{3}$$

$$\sum_{i\in I} x_{i,j,t} \le 1 \qquad ; \; j \in J, t = 1,...,T \tag{4}$$

$$\sum_{j\in J_r}\sum_{i\in I} x_{i,j,t} \le 1 \qquad ; t = 1,...,T, r \in R \tag{5}$$

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

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

$$v_{i,j} \cdot y_{i,j,t} \le \sum_{\hat{t}=t}^{t+v_{ij}-1} x_{i,j,\hat{t}} \qquad ; \; i \in I, \; j \in J, t \in T \tag{8}$$

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 so no interruptions are allowed. In addition, note that the objective function (1) minimizes the total execution time, ultimately aiming for increased productivity. The mathematical program presented could be further extended to incorporate additional considerations such as precedence relations between the walls and cost constraints, detailed in Florez [6].

3.1. *Labor productivity function*

Let's look closer how to determine the number of time periods that a crew j takes to build a masonry wall i, that is parameter v_{ij}, which is calculated using the productivity function. As detailed in Section 2.1, it was found that the productivity of a crew is affected by the compatibility (c_j), the suitability (s_j), and the craft (k_j) of the crew. Note that the higher the compatibility, the suitability or the craft the higher the productivity. Therefore, the productivity function is expected to be a function of these three parameters, $F(c_j, s_j, k_j)$ and common sense dictates that F should be an increasing function of its arguments,

$$\partial F/\partial c_j \ge 0, \quad \partial F/\partial s_j \ge 0, \quad \partial F/\partial k_j \ge 0$$

In Florez [6], the productivity function is given by equation (9). The function was used in a medium size construction site and its results were similar to the ones expected (with the data in hand) so these assumptions apply.

$$F = 1/3(c_j + s_j + k_j) \tag{9}$$

This can be considered a first order approximation to F (Taylor polynomial of degree 1), and in this case we justify its use by the fact that the site area where it was used was of moderate size. In a more general context we could have used as a first approximation the more general equation (see equation 10):

$$F = \alpha \cdot c_j + \beta \cdot s_j + \lambda \cdot k_j$$

It may be expected that α, β, λ might be different, but further investigations are needed to properly define these parameters. We expect F to be nonlinear, and its nonlinearity should manifest itself in more complex building scenarios. In the last section we discuss the possibility that F satisfies universal convexity properties. To calculate the time that it will take crew j to build a wall, lets define u_i as the total number of units in wall i. The time is given by equation (11):

$$v_{ij} = \frac{u_i}{F(c_j, s_j, k_j)} \tag{11}$$

This study is proposing a productivity function (alongside the model) in terms of the compatibility, suitability, and craft scores of the masons in a crew. Function F given by equation (9) was proposed for a number of reasons:

- F is a linear approximation since it is expected that the suitability, compatibility, and craft scores will contribute to affect the productivity. It is not the product of the scores because it is not expected that these may have such a significant reduction in the productivity. If it had been the product of the factors, even for a slight reduction of the factors the total productivity will be considerably reduced which does not truly reflect the capabilities of the masons. The masons are qualified to place units in a wall because they are trained to be masons.
- The coefficients of the three factors (compatibility, suitability, and craft) in the function are assumed to be the same since without any further information it is natural to propose that the factors influence the productivity equally. Therefore, the productivity will be the mean value of the factors. In this particular case [6], there is no more data in hand so these assumptions apply. Note that the case study was developed in a site of moderate size. The function and its coefficients may change given a different size and also further studies can be developed to determine the coefficient for each one of the factors.

3.2. *Convexity properties of the productivity function*

It is expected that when the function F is expressed in terms of compatibility (any other parameters fixed), then it will have a universal form. The shape of this function may be of interest, as it may have implications over how careful the selection of crews must be. Since there is no way, founded on theoretical grounds to determine the shape of the productivity function in terms of compatibility, an example is used to show how this information could be of use. Note that the shape could be determined by experiments using a sensitive enough Likert scale.

Let us assume that the shape of the productivity function F has been determined to be concave as shown in Figure 1. More rigorously, F satisfies equation (12) for all the values that it is defined and it may or may not be a continuous function, as compatibility can take on values on a discrete scale. Therefore, there is a value of compatibility c_0 (see Figure 1) above which, the process of selection of the crews will not produce a significant increase in productivity. However, below this level much more attention should be paid to the selection of crews as this could be meaningful for the productivity output.

$$F\left(s \cdot c_1 + (1-s) \cdot c_2\right) \geq sF\left(c_1\right) + (1-s)F\left(c_2\right) \qquad ,0 \leq s \leq 1 \tag{12}$$

In Figure 1, notice that the difference in productivity for the crews whose compatibility is below c_0 is much bigger than the difference in the case of the crews whose compatibility is above c_0. For instance, if crew 3 were to be chosen over crew 4, the impact on productivity would not be as significant as if crew 1 was chosen over crew 2. So in this case, having to select two crews to optimize productivity (assuming there are only two choices: crew 1 and crew 4 or crew 2 and crew 3), the selection could be the two crews whose compatibility is close to the c_0 value, instead of trying to select one with an outstanding score and one with a score far below c_0. So if the selection is between crew 1 and crew 4 or crew 2 and crew 3, the heuristic would make the second choice. This will be of course reflected in the choices made by the model in this paper; but the choices made following this heuristic in more complicated examples should not differ significantly from the optimal one. These results might be good enough for practical purposes and could be used to simplify the optimization process or even to make a rough guess on how to form the crews.

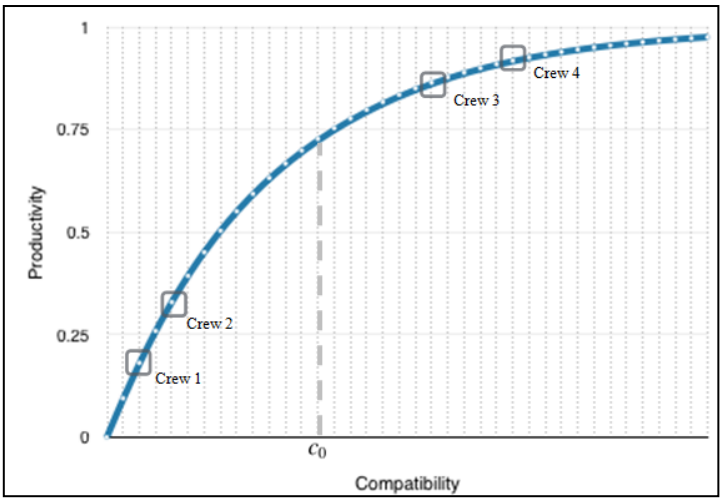

Figure 1- Productivity function

The example above also shows that the simple fact of knowing the shape of the productivity function (not without knowing its exact values), may serve as an heuristic to make decisions on how to form crews. As shown above, just knowing that the productivity function is concave, it is preferable to have crews that have medium/average compatibility scores than having some that have mediocre compatibility scores and some that have outstanding compatibility scores. If the productivity function were convex, a better strategy would be to start choosing as many outstanding crews as possible, not paying too much attention to the fact that some crews may have mediocre compatibility scores. Note that the more concave or the more convex the productivity function is (as a function of compatibility), the better these heuristics will work. However, the closer the productivity function is to a linear function, working with a full-fledged optimization model becomes a more critical issue.

On the other hand if there is a more precise knowledge of the productivity function, the optimization process proposed could be modified not only in the sense of giving heuristics as above. Indeed, in simple cases instead of going for a full optimization with all the constraints that might be added to the model to make it as precise as possible, the process could be simplified by just maximizing the number of crews that have a compatibility score above a certain threshold (eliminating some other constraints) or by introducing penalizations for not using crews with compatibility scores close enough to a certain threshold. In other words a full-fledged model for a simple construction case can be thus simplified without losing significant information and this can be done in principle by a capable superintendent, who has been taught to how do so.

4. Conclusions and discussion

The crew allocation process in masonry construction is challenging. 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. A mixed-integer program was developed to allocate crews and schedule walls. The model not only determines which crew is assigned to each wall but also the masons in a crew and the times the crews are working in a specific wall. Alongside the model, a productivity function was proposed to mathematically define the factors that most affect masonry productivity and the factor's effects. Through a series of examples it was shown that the shape of this function is of interests because it may have implications over how careful the selection of crews must be. Such findings can help understand what aspects for instance influence crew formation and what should be the focus of managers when forming crews in construction and other group teams.

Consequently the question we must raise now is the following: is the shape of the productivity function universal? By universal we mean that, aside from its exact values, it does not depend on the building techniques and it will be consistent. In other words, two masons that have the same compatibility would be expected to have a similar productivity record every time they are grouped in a crew. If this universality is found, we believe that it would be an outstanding discovery. We ask the reader to think about the utility function in economics, whose shape is universal (concave), and that it is determined from basic economic principles. Hopefully one day we will find firm theoretical grounds based on the knowledge contributed by other social sciences to predict the shape of our productivity function.

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