Towards Cost-Time-Quality Optimized Construction Plans: An Experimental Approach

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***Abstract*—Unrealistically squeezing construction schedules often compels constructors to compromise quality. Despite its recurrence, this fact is repetitively overlooked by planners whose principal concern is time vs. cost schedule optimisation, while disregarding the stance of quality in the equation. The mission of quality management is rather handled at the construction stage and not at the planning stage. In the light of this problem, this research contends to the need for reverting QM upstream at an early planning stage, by developing schedule solutions that not only optimises time vs. cost, but also quality criteria. This paper strides a step towards achieving this goal, by building an experimental design consisting of 13 runs, which, after implementation, will find the optimum crew size and (imposed) productivity rates so as to achieve the lowest cost while keeping the quality and production efficiency at their highest applicable levels. The primarily planning phase of the experiment is illustrated in this paper including the choice of factors, response variables and finally building the experimental design using MINITAB software as an experimental designing tool.**

***Index Terms*—Defects, quality, productivity, optimization, construction planning.**

I. Introduction

Quality in general is the degree of excellence of something, while in construction industry, quality is evaluated as the executed work's compliance with the international quality standards ISO 9000, especially in the clauses of inspection and testing, control of nonconforming products and handling, storage, packing and delivery of materials as stated in [1]. Degradation of construction quality does not only affect the contractor's reputation, it also has an impact on the appearance, functionality, and sometimes safety of a project. Subsequently, these effects raise the idea of considering quality records of previous activities in planning future ones, in a way that integrates quality control with planning in a single comprehensive approach, rather than merely applying a separate quality control system. The idea becomes a need in the case of compressed recovery plans where quality becomes highly prone to degradation due to contractors prioritization of time and cost over quality. As such, the majority of previous research merely emphasize on cost-time trade-off analysis [2]-[6], but very few stress on cost-time-quality optimization.

Cost-time schedule optimization entails identifying the optimum crew size, and the optimum pace of production, for each task. Estimated productivity rates denoted by planners typically become imposed on crews by site supervisors during construction. The term *imposed productivity rate* will be used in this paper to refer to the expected rate of progress imposed on crews during construction by the means of a planning decision regardless of whether that decision was realistic or not, and regardless of the implications held by this decision. For planners, matching the optimum crew size, with the optimum expected/imposed productivity rate is yet a challenge. For instance, assigning a crew size smaller than the optimum with higher imposed productivity rates results in low quality, due to unrealistic expedition of work, which needs additional repair work and time, yielding a relatively slow overall productivity. On the other hand, a crew size higher than the optimum leads to an overloaded workspace situation which causes additional inefficient cost. This stresses on the need for optimizing crew sizes and imposed productivity rates in a way that accounts for cost, time and quality at the same level of importance. Previous literature proposed a multi-objective optimization approach to solve time-cost-quality tradeoff problems in general [7]. This paper contributes to previous body of research by the formulation of experimental means for studying the effect of different compositions of crew sizes and imposed productivity rates on cost, time and quality of construction tasks.

Particularly, this paper experiments ceramic tiling activities using a Central Composite Design (CCD) to find the optimum setting of crew sizes and planned productivity rates of each trade in order to incur the minimum cost while maintaining acceptable levels of quality and overall productivity. CCD is used because the quality data should be statistically analyzed as done in [8] and [9]. Such investigation would require the least number of experimental runs due to the difficulty of conducting live quality/productivity experiments at construction. CCD is deemed fit for this particular purpose, as it yields significantly valid results using minimal number of experimental runs.

II. Scope Determination

The major phases to complete an experiment are planning, conducting and analyzing the experimental results [10]. The experiment is planned to be implemented on a construction project of commercial and residential building at its early stage. This paper describes the primarily planning phase of ceramic tiling optimization experiment which includes:

1) Choice of factors, levels, and ranges.
2) Selection of Response variables.
3) Choice of design.

Each of these steps are discussed in further detail in the

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forthcoming sections.

III. Choice of Factors, Levels, and Ranges

There are two groups of factors in this experiment, design factors and held-constant factors.

A. Design Factors

The design variables are the ones of our interest. They are known to have an impact on one or all of the experiment response variables. Our aim is to find the optimum settings for these variables in order to obtain the desired optimum responses. These variables are:

1) Crew Size (CR)

The crew size is the number of masons assigned for each run of the experiment, it depends on the area of workspace as mentioned previously.

2) Imposed Productivity (IP)

The imposed productivity is defined as the productivity forced on each mason by the site supervisor. It depends on the level of skill required for the work (artistic work for example requires more time) and also depends on the work status (delayed work usually leads to forcing higher productivity).

To obtain an applicable range of crew size, the workspace area is determined to be $300m^2$ for each experimental run. The case of overloaded workspace which increases the cost & decreases the overall productivity is determined based on the contractor's site engineer, which was regarded as an expert's opinion. The site engineer estimated that above 10 mason's in a $300m^2$ area would overload the workspace and result in minimal productivity increases, or possible productivity drops.

On the other hand, the range of the imposed productivity is determined based on historical data of previous projects, which varies from a type of work to another, and also depends on the weather conditions, labor skills & the workspace. In this experiment we have the following conditions:

1) Country: UAE
2) Weather: average
3) skills: average
4) Workspace : 300 m^2

From the above conditions, the range of the imposed productivity ranges between 6 to 22 m^2/day/mason.

Accordingly, the levels of the design factors that are used in each experimental run are shown in the Table I. The experiment will be designed using Minitab commercial software which requires an input of coded and uncoded values of the levels. The coded values 1, 0 and -1 represent the high, medium and low values of each factor's uncoded levels, respectively.

TABLE I: Levels of Design Factors

Coded levels		Uncoded Levels	
CR	IP	CR (masons)	IP (m^2/day/mas)
-1	-1	6	9
0	0	8	12
1	1	10	15

B. Held-Constant Factors

These factors are known to affect the responses of the experiment, however, they are not of our interest so they're held to certain levels that suit the experiment's purposes. These factors are:

1) The quantity of ceramic tiles for each run (QTY):

Quantity plays a major role in deciding the range of applicable crew size. The quantity of ceramic is held to a constant value for each run, because big differences between quantities may cause nuisance effect on the experimental results. A quantity of ($300m^2$) is determined in a way to get an applicable range of crew size.

2) No. of working hours per day:

The number of daily working hours is used to calculate the productivity, it depends on the country regulations and work conditions. In UAE, the regular working hours are (8 hours/day).

3) Ceramic tiles unit rate:

This is used to calculate the material cost, it depends on the kind and origin of the ceramic. The kind of specified ceramic in this project is Roma Glossy Ivory (60X60cm) and its unit rate is 20 AED/m^2.

4) Masons' hourly rate:

The hourly rate is used to calculate the labor cost, for masons in the contracting company, which is 10 AED/hr.

5) Cost of delay per hour:

In order to compute the overall cost of the activity, we need to consider the worst case scenario, where the activity is on the critical path and delaying it would result in a project delay penalty. For the sample project, the penalty is 16000 AED/day, which equals 2000 AED/hr.

6) The weather Conditions:

The temperature & humidity plays a major role in determining the actual productivity in the region as concluded in [11]. The weather conditions are assumed to be within the convenient limits as the activity will be done throughout the winter in UAE.

IV. Selection of Response Variables

A. Quality Rate (%)

The *Quality Rate* is used to warrant consistent means of quality assessment, so as to maintain the reliability of the collected data. This rate is defined in consultation with the site engineer, and is represented as a percentage depending the number and type of defects in the executed ceramic tiles that need to be repaired. The defined defect types and their relevant *Quality Rates* are listed below:

1) Hollow-sounding tiles: 25%
2) Inequality of the grouting thickness: 17%
3) Installation of tiles with broken edges: 20%
4) Installation of tiles with slightly mismatched colors: 13%
5) Exceeding the accepted limits of leveling: 25%.

B. Production Efficiency (%)

Production efficiency (PE) is the ratio of actual productivity (AP) to the imposed productivity (IP), as shown in Equation 1:

$$PE = (AP/CR)/IP * 100\% \quad (1)$$

where:

PE: Production Efficiency (%)

AP: Actual Productivity of the Crew (m^2/day)

CR: Crew Size (masons)

IP: Imposed Productivity on each mason (m^2/day/mason)

It should be noted that the actual productivity takes into consideration the original time in addition to the time of repairing the defected ceramic tiles, in case of rework. The actual productivity is calculated as shown in Equation 2:

$$AP = WH * QTY/TD \quad (2)$$

where:

WH: Working Hours per day (8 hrs/day)

QTY: Total Quantity Done (set to be 300 m^2)

TD: Total Duration of work (hrs)

The Total Duration is Calculated using Equation 3:

$$TD = ID + RD \quad (3)$$

where:

ID: Imposed Duration (hrs) is calculated using Equation 4:

$$ID = QTY/(CR * IP/WH) \quad (4)$$

RD: Repair Duration (hrs) is calculated using Equation 5. This an additional duration to repair the low quality work (defects).

$$\text{RD} = (1 - \text{Quality}) * \text{ID} \quad (5)$$

C. Overall Cost (AED)

Cost reduction is one of the three aims of this experiment. The overall cost of each run of the experiment is the summation of four sources of cost: material cost, labor cost, repair cost and delay cost.

$$Overall\ cost = MC + LC + RC + DC \quad (6)$$

where:

MC: Material cost for each run (AED) is:

$$MC = QTY * UNIT\ RATE \quad (7)$$

LC: Labor cost for each run (AED) is:

$$LC = TD * LABOR\ RATE * CR \quad (8)$$

RC: Repair cost for each run (AED) is:

$$RC = (1 - Quality) * QTY * Unit\ rate \quad (9)$$

DC: Delay cost for each run (AED) is:

$$DC = Delay\ rate * RD \quad (10)$$

V. Choice of Design

Response surface design is set of improved optimization techniques used in Minitab software [12]. It provides an accurate, yet simplified method to determine the optimum settings of the two factors in order to maximize the quality and minimize the cost and the loss of productivity.

Available response surface designs include the Box-Behnken Design and the Central Composite Design. The Box-Behnken design doesn't have factorial points, it's almost rotatable and needs fewer experimental runs than the central composite design. However, the Box-Behnken design needs at least three continuous factors to be implemented. Therefore, the Central Composite Design (CCD) will be used.

A. Central Composite Design (CCD)

The CCD for two factors consists of :

1) Four factorial points (full factorial points), these points have the coded levels of 1 or -1 .
2) Five center points as default by MINITAB. We will keep the default to get an adequate estimate of error.
3) Four axial points with a default α calculated by (11):

$$\alpha = \text{No. of factorial points}^{1/4} = 4^{1/4} = 1.414 \quad (11)$$

where α is the distance between the center point and the axial point.

Here there are two determinations to construct the design:

1) The number of center points. Center points provide a good estimation of the error, and thus provide more accuracy. We'll keep the default No. = 5 center points, as suggested by [12].
2) Alpha for the axial points is the distance between the center point and the axial point. It's preferable by [12] to keep it 1.414 in coded units to make the model rotatable. However, it is not applicable for the types of factors that we are dealing with:

Crew size; 8 + (1.414 ∗ 2) = 10.83 masons

We use 11 masons, so α = 1.5

Forced productivity; 12 + (1.414 ∗ 3) = 16.242

A visual description of the CCD is shown in Fig. 1

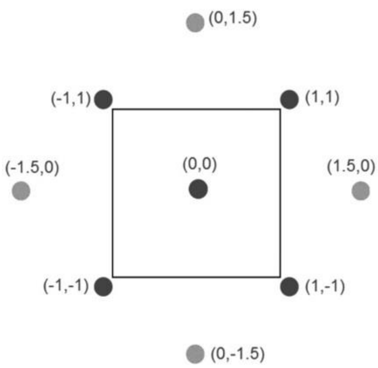

Fig. 1. Central composite design (coded values).

Using MINITAB software, a response surface design is created with the following settings:

1) Type of design: CCD
2) Type and Number of factors: continuous factors = 2
3) Alpha = 1.5
4) Center points = default = 5

5) Type of replication: non replicated design

6) Number of Blocks: no block.

The final design can be presented as the following experimental design (Table II), which shows a total number of thirteen runs with both the coded and uncoded levels of factors.

TABLE II: CENTRAL COMPOSITE DESIGN OF CERAMIC CREW EXPERIMENT

CENTRAL COMPOSITE DESIGN					Uncoded Factors Levels	
StdOrder	RunOrder	Blocks	Crew	Forced Prod.	Crew	Imposed prod.
6	1	1	1.5	0	11	12
13	2	1	0	0	8	12
11	3	1	0	0	8	12
4	4	1	1	1	10	15
2	5	1	1	-1	10	9
12	6	1	0	0	8	12
10	7	1	0	0	8	12
5	8	1	-1.5	0	5	12
1	9	1	-1	-1	6	9
7	10	1	0	-1.5	8	7.5
9	11	1	0	0	8	12
8	12	1	0	1.5	8	16.5
3	13	1	-1	1	6	15

This table is the final result of the experiment's planning phase.

The above thirteen experiments will be implemented in a random order to find the corresponding values of the three responses in our experiment. Afterwards, the results will be analyzed so as to determine the optimum settings of both, the crew size and imposed productivity, in a way that minimizes the overall cost while keeping both production efficiency and quality at their highest achievable levels.

VI. CONCLUSION

The experimental design provided by this paper is a flexible design that can be applied on other types of activities by changing the factors to retrieve the same three responses. The optimization results of multiple activity types can build a comprehensive set of optimization models for the project, which can be used in building a realistic compressed plan that procures the best out of the available resources.

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