Optimization Model for Construction Processes in Residential Buildings

Mahmoud Y. Abukmail, Rifat N. Rustom, and Hasan KH. Abujamous

Abstract—Residential building projects have a considerable economic standing in the construction industry in Gaza Strip. Many previous researches demonstrated that conventional planning and scheduling methods that are commonly used do not achieve optimum resource plans, which have direct influence on the project costs and duration. This paper integrates simulation and optimization of construction processes as a key solution for planning and scheduling residential building projects in terms of time and cost with the optimum number of resources. A general simulation model was developed for typical residential building projects with most possible scenarios. The model was developed by formulating a conceptual model that represents the typical construction processes. The conceptual formulation was then modeled using ARENA simulation software. The simulated model was verified and validated. The optimum number of resources was determined based on the minimum cost and availability constraints using OptQuest. A visual basic interface was developed to facilitate using the model. The developed model was found to be an effective tool for planning and scheduling residential building projects with complex relationships between activities and considering the uncertainties in activities’ durations. The optimization process achieved 7.5% decrease in the total cost from the actual cost through finding the optimum number of resources. The practical application of the model helps the construction firms and the planners to build effective plans with better accuracy for the utilization of resources in residential building projects.

Index Terms—Optimization, Simulation, Residential buildings, Construction, ARENA software.

I. INTRODUCTION

It is an intuitive matter to consider resources in construction operations as a crucial element. This level of importance came from the essential contribution of resources to the success of the project plan in terms of cost and duration. Residential Building (RB) projects are classified as repetitive activities projects, which have similar activities that are repetitively performed from unit to unit[1]. The main challenges of planning and scheduling of RB-projects are as follow: getting the optimum project duration subject to resource continuity constraints and minimum resource cost; considering the complex relationships in how resources are managed to keep resources working without idle time[2]; and the stochastic approach for activities duration[3, 4]. Therefore, there is a need for better tools for planning and scheduling of repetitive projects which makes it easier for the user to create better plans with higher accuracy.

Using simulation modeling is found to be widely accepted by different industries and sectors, e.g. military, manufacturing and service that supporting a decision-making[5, 6]. Simulation technique is a powerful tool to analyze and design complex systems i.e. construction operations with dynamic data[2, 7]. In addition, simulation allows complex relationships between activities, which specifically consider resource usage, and uncertainties. This paper developed a general optimization model as a key solution for planning and scheduling RB-projects in terms of time and cost with the optimum number of resources. The model used OptQuest-ARENA as an optimization tool. The developed model supports engineers to estimating project’s duration, resources’ cost and optimum number of required resources with adequate level of confidence. In addition, the model provides a visual basic interface to facilitate data entry and use the model.

II. LITERATURE REVIEW

The main challenge that aspired in managing construction projects is completing the project with the least amount of time and at the lowest possible cost. Sawhney [8] pointed that simulation can provide an excellent solution to construction scheduling. Shi [9] handled simulation usefulness from the perspective of describing complicated processes,
where the relations are difficult to define causally, or an analytic model would be too difficult to solve. Furthermore, Cheng and Feng [10] pointed that simulation technique has been proven useful in analyzing the stochastic perspective of the construction operation. The non-deterministic nature of construction projects is one of the most complicated factors that are often simplified or neglected by modelers [11, 12]. Many deterministic approaches such as linear and dynamic programming fail to provide a result with confidence because of the simplification [12, 13]. On the other hand, simulation is considered an excellent tool for the stochastic problems because the effect of uncertainties in construction projects can be modeled and assessed [12, 14]. As a stochastic tool, Oloufa, et al. [15] found that simulation modeling can provide a powerful tool for the study and analysis of construction projects.

AL-Tabbaa and Rustom [16] found simulation an effective approach for developing multiuse simulation modules for estimating project durations at the planning phase for infrastructure projects. Ebrahimi, et al. [17] developed a detailed simulation model capable of capturing the complex variables impacting the productivity of tunneling construction projects. AL-Hams [18] developed a simulation model for change orders occurrences and their impact on cost, time, and productivity for building projects in the Gaza Strip. Moreover, he concluded that simulation is an effective tool for showing the factors causing change orders and forecasting their impact on the building projects. Lu and Olofsson [1] developed a continuous flow simulation model in order to overcome the deterministic nature for activity duration. In addition, they used different distribution functions for calculating the activities durations in each activity. Srisuwanrat [19] presented the Sequence Step Algorithm (SSS-AL), a simulation-based scheduling algorithm for repetitive construction projects with deterministic and/or probabilistic activity durations. SSS-AL is capable of scheduling repetitive projects under variability and uncertainty while maintaining continuous resource utilization. Song, et al. [7] proposed a framework of real-time simulation for modeling heavy construction operations. In this framework, dynamic data from construction operations are constantly captured and fed into a process simulation model for short-term scheduling purposes. Cho and Eppinger [2] presented a simulation model for managing complex design projects. Their model computes the probability distribution of lead time in a stochastic, resource constrained project network where iterations take place among sequential, parallel, and overlapped tasks. They concluded that simulation is excellent tool for evaluating different project plans and for identifying strategies for process improvements. Rustom and Yahia [20] found that the use of simulation an effective tool for estimating production rates in an attempt to prepare optimal time schedules. They took Gaza Beach-Camp Shore Protection Project as case study to demonstrate how to estimate effectively the production rates of labour and equipment during the implementation of the project activities and to estimate the duration of the project using process simulation. Al-Helou [21] concluded that simulation is able to empower the planner to be fully aware with the used resources and all of their related features during the project, just like the execution environment. He developed an optimization model for infrastructure projects to demonstrate the resource utilization effect on cost and duration of projects.

The use of simulation for analyzing and planning construction projects is slowly gaining acceptance in the construction industry [22]. The principal reasons include the complexity of simulation tools (programs), and the lack of familiarity of simulation to practitioners [23, 24]. To meet these requirements, many researchers proposed user-friendly simulation environments. AL-Tabbaa and Rustom [16] demonstrated examples about how simulation interaction interface can contribute to the efficiency of using the simulation technique. Srisuwanrat [19] presented a Graphical User Interface (GUI) to facilitate to schedulers creating simulation models for repetitive projects. Cheng and Feng [10] integrated simulation with Genetic Algorithm to develop a user-friendly computer simulation system (Genetic Algorithm with Construction Operation Simulation Tool), as attempt to find the best resource combination for the construction operation.

### III. METHODOLOGY

The major objective of this study is to introduce a general optimization model for planning and scheduling residential building projects to find the optimum number of required resources with adequate level of confidence. The authors followed the procedures viewed in [25], for building the model, as shown in Figure 1, which is divided into three stages:

*Model development:* a general verified and validated simulation model was developed. The model simulates on-site construction activities in
terms of time and resources' cost using ARENA software.

**Optimization process:** the optimal number of resources were determined based on minimum cost using OptQuest-ARENA as an optimization tool.

**User Interface:** a visual basic user-friendly interface was integrated with the model to assist users to easily input their data. This interface requires no previous simulation knowledge to operate the model.

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### IV. MODEL DEVELOPMENT

One of the main factors behind building any effective simulation model is the general concept, which explains how a real environment would be converted into a virtual one[26]. The model building was divided into four sequential steps as follow:

**A. Input Data and Analysis**

Unlike most of the conventional planning and scheduling methods, the simulation model can be fed with more detailed information regarding productivity rates, cost rate, quantity and priorities for any activity.

**A.1. Production rates:** productivity for resources is considered the most essential input data for any activity to compute the stochastic durations. The production rates were collected for each resources in each activity based on ten working hour per day.

**A.2. Activities’ relationships:** according to the nature of RB-projects, each activity has multiple predecessors and successors. The activity may be linked with more than one activity in different locations. The start time of the activity was controlled by the availability of resources.

As soon as adequate data are collected a preliminary analysis of the data was performed. The analysis data involves the computation of various empirical statistics from the collected data. Eighteenth points for productivity were collected which was as three points (minimum value, most likely value, maximum value) for each reading. One of the most features that distinguish ARENA software is to consider the realistic nature of data through providing data analysis facilities via its Input Analyzer tool. According to the nature of collected data, the triangular distribution was the most suitable function for the resources’ production rates.

**B. Conceptual model formulation**

Robinson [27] defined the conceptual model as “the abstraction of a simulation model from the part of the real world it is representing (the real system)”.

After studying all requirements for planning and scheduling the RB-projects and the simulation consideration the conceptual model was developed, which reflects the logical relationships between activities and describes the general mechanism for RB-projects, as shown in Figure 2.

**C. Typical model building**

Once the conceptual model is built, it becomes easy to construct the general hierarchy of the typical simulation model that describes how the system components will be modeled. The generic model was divided into four sequential levels that are embedded in each other to formulate the final simulation model that reflects the conceptual model, see Figure 3.

**C.1. Model level:** represents the generic model that reflects the general system logic for the entire project. It consists of many groups of blocks connected to each other. The model was developed through generating one entity representing the project. The entity was transmitted from one block to another until all activities in each block have been executed.

**C.2. Blocks level:** consists of a group of sub-models that are logically connected to each other. The logical connections depend on the different...
scenarios that are agreed at the beginning of the work by the planner.

C.3. Sub-models level: composed of a number of interrelated activities (modules), which are logically connected with each other. All possible scenarios in RB-projects will be simulated through the sub-models. Some of these sub-models are repeated in each block for simulating the repetitive part.

C.4. Modules level: It is considered the key element for the simulation model. The modules are considered as flow of logic that simulates different construction activities. Modules were classified into three types: the first type is dedicated to data entry (Assign modules). The second type is related to build the logical relationships in the simulation model that contains (Separate, Batch, Decide modules). The last type is (Process module), which represents the activity.

The developed model was composed of twelve ARENA blocks: project start, mobilization and excavation, footings, underground works, basement floor, ground floor, mezzanine floor, typical floor, roof floor, assemble block, staircase and external finishing and handing over. Through these blocks, all activities of the project will be simulated. Each block is responsible for simulating part of the project. They are linked with logical relationships that suit the nature of RB-projects as shown in Figure 4. All possible scenarios were simulated to build a general simulation model that satisfies the nature of the RB-projects. The user chooses between these scenarios according to his case and reflects his choice to ARENA model via “Decide module” using the interface. For example, the model is valid for three types of footings (isolated, combined...
footings and mat foundation), that the user chooses between them. The model begins with the “project start” block, which is considered as starting point for the flow of the entity through the model. It has one sub-model with two basic functions: Create the entity via “Create module”, which creates one entity representing the entire project (Building), and assigns the required data through “Assign module” as attributes. For entering all variables related to site conditions and quantity of each activity, 104-assign modules were designed.

D. Model Verification and Validation
During the model building phase, it is essential to ensure that the simulation model operates as intended and that the model actually runs. This process is known as model verification[25]. Verification should be considered as a continuous process rather than a one-shot effort[22]. So the verification process was executed by comparing each block of the model versus the applied traditional schedule using the critical path method (CPM) for a real case. If these results are close to actual results, then this means that the simulation model has correct logical relationships and probability distribution functions. In addition, the logical relationships between activities were tested by tracking each start and finish dates for each activity using MS-Excel. Furthermore, all activities were drawn in Microsoft Office Project (MS-Project) to ensure that there is no misallocation happening in resources.

After ensuring that the model was built correctly, validation process started. Chung [25] defines the model validation as “the process of ensuring that the model represents reality at a given confidence level”. Validation should be done for the entire model[29]. In this paper, two types of validation were used. The first is face validity, which was achieved through a cyclic model review and improvement process with the assistance of a number of project managers and site engineers. The second is statistical validity that was achieved by comparing the model’s results with CPM plan for an actual case study.

A residential building project in Gaza Strip was selected to be a representative case study that was modeled by ARENA software. The project consists of five typical floors, basement, ground, mezzanine and roof. The area of ground floor is 788 m², the area of typical floors is 861 m², and the area of the roof is 490 m². The basement and ground floors were designed as service places and warehouses. Other floors were residential floors. The type of foundation was isolated and combined footings. The project includes all internal and external finishing works. The actual plan for this case study was built using MS-project. The MS-project depends on deterministic durations for activities. Moreover, the MS-project produces only one simple planning attempt. For instance, the total duration was (290 working days) and the total resources cost equals ($ 204,880). The simulation model was
run 100 replications with confidence level 95% using ARENA. Table 1 shows the results of the simulation model.

Table 1: Simulation results

<table>
<thead>
<tr>
<th>Values</th>
<th>Average</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (days)</td>
<td>278 ± 3</td>
<td>239</td>
<td>314</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>202,776 ± 1,875</td>
<td>182,631</td>
<td>229,451</td>
</tr>
</tbody>
</table>

It is clear that the differences between the results of the simulation model and the actual plan results are relatively small (about 2%). Also, it is clear that the resources’ costs of the simulation model are close to the actual resources’ costs (about 2%). In addition, by face validation, the simulation result was acceptable. So it is demonstrated that the model was valid and was designed properly in terms of time and cost.

It is noteworthy that the estimated duration (simulation results) depends on the distribution functions for the activities durations, which were considered the main power of the simulation in planning and scheduling RB-projects. Moreover, the simulation results provide more support by generating many planning attempts at each replication. In addition, the model has the ability to define such uneven levels of priorities for the performed activities. All of the mentioned characteristics of the simulation model input features make it advantageous regarding the outputs quality.

V. OPTIMIZATION PROCESS

In terms of finding an optimum number of the resources crew with minimum cost and sophisticated constraints, the optimization process is a valuable tool. The designed model integrates simulation and optimization by using OptQuest-ARENA. OptQuest is an optimization tool that enhances the analysis capabilities of ARENA by searching for optimal solutions within simulation model to satisfy the defined constraints. OptQuest employs meta-heuristic analysis tools. It includes sampling techniques and advanced error control to find better answers faster. And, it incorporates state-of-the-art algorithms based on Tabu search, scatter search, integer programming, and neural networks [30].

The optimization process was carried out through four sequential steps: define controls, select required responses, define constraints and define the required objective.

A. Define controls

The optimization process begins with the identification of the resources constraints, which is called controls in the OptQuest environment. The optimization process is controlled by the selected controls (resources) and their values which are provided to the ARENA model. Three resources were selected as controls in the optimization process (shutter crew, mason crew, plastering crew) that are considered as permanent resources owned by a construction company. After selecting the required resources, the capacities for each resource (upper and lower bounds) that will be used in the optimization can be specified.

B. Select Responses

The objective function and constraints may depend on the outputs of the optimization, and therefore, they are based on responses. The Responses node of the OptQuest tree displays the hierarchical structure of responses in ARENA. Any selected response can be used to create constraint and objective expressions. In addition, all selected responses will be shown in the solution details view, which can be displayed after an optimization process completes. The selected responses in the model were:

- System.Total Cost (for objective expressions) that equals all entities costs plus all resources costs (idle and busy costs).
- All Entities.Total Cost (for view in the results) that equals entity value added costs (busy resources cost) plus waiting cost.
- Entity.Total.Time (for constraint expression) that means the entire simulation time.

C. Define Constraints

The optimization can run without defining any constraint. However, including constraints (if appropriate), which define relationship among controls (resources) or responses, increases the efficiency of the search for optimal solutions. The main constraint in the model was the total time as in the contractual requirements (less than or equal 290 day). A feasible solution is one that satisfies all constraints. Infeasibility occurs when no combination of values of the controls can satisfy a set of constraints. The infeasible solution occurs when failing to satisfy the problem constraints and this does not imply that the problem or model itself is infeasible.

D. Define Objective

In OptQuest, only one objective can be defined for the optimization process representing the model’s goal in terms of the assumptions and controls. The objective is either to minimize or maximize the quantity. OptQuest’s job is to find the optimal value of the objective by selecting and improving dif-
 Different values for the controls. The model objective was minimizing the total costs of the project. Table 2 summarizes the OptQuest input data.

<table>
<thead>
<tr>
<th>Controls</th>
<th>Lower</th>
<th>Suggested</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter Crew</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Mason Crew</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Plastering Crew</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Constraints</td>
<td>(Entity) Total Time ( \leq 290 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Objective</td>
<td>Minimize Total Cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The other resources capacities still as entered in the model and do not change during the optimization process. The model was run 100 simulation runs and the number of replications was varying between 2 and 6 replications per simulation.

VI. RESULTS AND DISCUSSION

Once the optimization process has been defined completely, the optimization can run. OptQuest evaluates the responses from the current simulation run, analyzes and integrates these with responses from previous simulation runs and determines a new set of values for the controls, which are then evaluated by running the ARENA model. This is an iterative process that successively generates new sets of values for the controls. The process continues until the optimization is stopped. When the optimization is completed, the best solution will be displayed. The best solution shows the optimum number of resources in terms of the selected objective and defined constraints. Table 3 demonstrates the results of simulation run number 45 that represents the best solution.

<table>
<thead>
<tr>
<th>Resources Name</th>
<th>Lower</th>
<th>Solution</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter Crew</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Mason Crew</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Plastering Crew</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total Duration (days)</td>
<td>288</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>189,454</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The new resources capacities that resulted from the optimization were inserted again in ARENA model to run the simulation and find the dates (start and finish) for each activity. After that, these dates for each activity were entered into MS-project that directly plots the project’s schedule to ensure that no overallocation occurs in resources. Table 4 presents a comparison between the optimization results and the actual plan.

<table>
<thead>
<tr>
<th>Resources Name</th>
<th>Optimization results</th>
<th>Actual plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter Crew</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mason Crew</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Plastering Crew</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total Duration (days)</td>
<td>288</td>
<td></td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>189,458</td>
<td>204,880</td>
</tr>
</tbody>
</table>

As shown in Table 4, the optimization process achieved decreasing in the total cost (about 7.5%) from the actual cost and the total duration is still around the actual. Moreover, the optimum number of resources crews is less than the actual plan. This can be attributed to two reasons: the first reason is due to the exploitation of the resources by integration between simulation and optimization using the optimum number of resources with maximum utilization and minimum idle cost, the second reason is the divergence in managing the resources between simulation and CPM. Simulation depends on the concept of resources performing activities sequentially, which means that the whole simulation process deals with the available resources that were predefined in the resources’ pool without any overallocation of any resource. While CPM used the resource-leveling concept, which means “the logical relationships control the works”.

VII. USER INTERFACE

ARENA interoperates with Visual Basic for Applications (VBA) that is designed to enhance the user interaction with the Arena model. VBA allows custom procedures to be inserted into a model. These procedures may be used to allow for the manipulation of variables or delay times, change the number of replications, the number of resources and many other useful functions. In this paper a simple user interface was designed for data entry. The user interface was developed to facilitate the interaction of the user with ARENA software.

The interface screen was divided into nine forms; eight of them were used for entering all input data and the last form was used for specifying the required options for running the model.
A. General Project Data Form
The user chooses the suitable simulation options from the three options according to his case. The first option is “Use Simulation” which allows the user to run the simulation model with specific number of replications without optimization. The second option is “Use Simulation and Optimization” which enables the user to run the OptQuest program for optimization the processes. The final option is “Simulation with One Replication” that is used when the user needs to find the Tasks Form (start and finish dates for each activity) in Excel sheet. At the same form the user can define the available resources (capacity, busy cost and idle cost). The user can upload previously saved data file by clicking “Upload Data File” button, see Figure 5.

![General project data form](image)

Figure 5: General project data form

B. Typical Floor Form
This form was designed for the data entry for the modules related to structure and finishing modules within the typical floor block. Similarity, five forms were developed related to data entry for the earth works, basement, ground, mezzanine, roof floors, staircases and external finishing, see Figure 6.

![Typical floor data form](image)

Figure 6: Typical floor data form

C. Start Simulation Form
Through this form, the user will run the model according to the chosen option in “General Project Data Form”. Through the buttons “Back” and “Next”, the user can navigate between the various interface forms. The button “Save Data File” was designed to save all input data to reuse it at a later time in running the mode, see Figure 7.

![Start simulation form](image)

Figure 7: Start simulation form
VIII. CONCLUSION

The designed model used the integration between simulation and optimization as a key solution for planning and scheduling the RB-projects in terms of time, cost, and the optimum number of resources. The model can provide numerous planning alternatives, and optimize such cases according to specified constraints. Moreover, the model generates massive and detailed output reports that can build a complete planning vision. The results of the validation demonstrate that the model gives reliable results and it is an effective tool for planning and scheduling RB-projects with complex relationships and uncertainties in activities durations. The developed model empowers the users to optimize any of the applied case parameters using OptQuest-ARENA. The optimization process achieved decreasing in the total cost of about 7.5% from the actual cost while the total duration is still around the actual. The optimum number of resources crews is less than the actual plan, which is due to the good exploitation of the resources by integrating simulation and optimization.

The designed model treatsthe debility for managing resources by ensuring the continuous resource utilization within the project to reduce the idle time and the overall project duration. Furthermore, the model helps the construction firms to build effective plans with high accuracy.

REFERENCES


Mahmoud Y. AbuKmail has M.Sc. in Civil Engineering from Islamic University of Gaza in 2013. AbuKmail is a projects manager in El Jazeera Constructions Company for Engineering Consulting (JCEC). His primary research interests include Simulation, Construction Management, Neural Networks and Computer Applications in Construction.

Prof. Rustom has M.Sc. and Ph.D. in Civil Engineering from Drexel University in the U.S.A. in 1993. He is the Rector of the University College of Applied Sciences (UCAS). Prof. Rustom is former Vice President for External Affairs and IT at the Islamic University of Gaza (IUG). Prof. Rustom has research interests in Construction Management, Institutional Management and Development, Geosynthetics, and Concrete Technology.

Hasan KH. Abujamous has M.Sc. in Civil Engineering from Islamic University of Gaza in 2013. He is a project manager in El Jazeera Constructions Company for Engineering Consulting (JCEC). His primary research interests include Neural Networks, Simulation, Construction Analysis and Concrete Technology.