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Using Probabilistic Crew Production Rate to Simulate Schedule-Related Risks in Construction Projects

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Abstract: Risks are inherent in construction and therefore needs to be incorporated in construction project planning. To this end, existing stochastic planning models use historical activity duration data to model time uncertainties and simulate project durations. This approach does not take into consideration the impact of day-to-day changes on time-related risk factors (e.g. weather, labor availability, and trade coordination) and their associated uncertainties. Therefore, simulation of crew production rate can provide a more accurate representation of these time-related uncertainties. This paper therefore presents the development of a new stochastic planning model that uses historical crew production rate data to simulate both activity and project durations. The model uses Monte Carlo simulation with beta distributions to capture day-to-day and shift-to-shift changes in crew production rate. In addition, the model also considers the impact of sharing a limited pool of resources on the construction duration of a portfolio of projects rather than single projects. An application example is analyzed to evaluate the performance of the new model and demonstrate its capabilities.

1. Introduction and Background

Construction planners and schedulers need to consider the impact of several variable factors while scheduling construction projects. These factors include jobsite management conditions, weather, and resource availability among others. Each of these factors can have a significant impact on production rate and therefore the time needed to complete construction activities and processes. Furthermore, many of these factors can change from day-to-day and even from shift-to-shift resulting in unpredictable crew production rate rates. This uncertainty makes estimating activity and project durations a complex and challenging task. In addition, the need to consider limited availability of resources and/or sharing a limited pool of resources among a portfolio of construction projects adds to the complexity of this problem.

Several research studies focused on planning and scheduling construction projects under uncertainties considering different objectives and using different simulation methods. Most of these studies focused on stochastic scheduling of construction projects assuming unlimited resources (Hong et al. 2011, Lee 2005, Lee and Arditi 2006, Lee et al. 2009, Ökmen and Öztaş 2008); or under resource constraints (Sadeghi et al. 2011, Taghaddos et al. 2012, Vaziri et al. 2007, Zhang and Li 2004). Other research studies focused on investigating the tradeoff between time and cost for stochastic planning of construction projects (Feng et al. 2000, Isidore and Back 2001, Isidore and Back 2002, Khamooshi and Cioffi 2012). In addition, other research studies on stochastic planning of construction projects focused on: allocating a project contingency for time to the different activities (Barraza 2011); overcoming the challenge of extensive data requirements (Ökmen and Öztaş 2008); balancing strategic and operational perspectives (Peña-Mora et al. 2008); and integrating space constraints and crew options in the planning process (Chen et al. 2012).

Most of the aforementioned research studies simulated activity and/or project durations, using different methods and processes, in order to account for the time-related risk factors and their associated uncertainties. Therefore, despite the original contributions of these research studies, no reported research considered the dynamic nature of utilizing construction resources on a day-to-day basis and its impact on crew production rate. In addition, no reported research studies considered the impact of time-related risk factors and their uncertainties on planning a portfolio of projects competing for a limited pool of construction resources. Accordingly, there is a pressing need for a new model that covers these two important research gaps.

This this paper therefore presents the development of a new Productivity Simulation Model (PSM) that is capable of considering the impact of time-related risk factors that can affect crew production rate on a day-to-day or shift-to-shift basis. This is done by simulating crew production rate instead of project or activity durations. In addition, PSM is designed to provide resource utilization capabilities at three different levels, namely the activity-, project-, and portfolio-levels in order to facilitate sharing a limited pool of resources among a portfolio of competing construction projects. Furthermore, PSM takes into consideration the impact of extended working hours and/or additional working shifts on crew production rate and therefore on construction time and cost. The following sections of the paper present the development of the new productivity simulation model, an application example designed to illustrate the use of PSM and demonstrate its capabilities, and discuss the conclusions of this research and provide recommendations for future research.

2. Productivity Simulation Model

The main purpose of the new Productivity Simulation Model (PSM) is to evaluate and measure the impact of day-to-day time-related risks and their associated uncertainties on construction projects schedule and cost. To this end, PSM simulates the production rate of construction crews on a shift-to-shift basis. In order to achieve this objective, the model is developed using C++ and includes several modules under three main phases: input phase, simulation phase, and output phase. The following subsections describe the development of each of these phases.

2.1 Input Phase

The main purpose of this phase is to collect and prepare the data needed for simulating crew production rates and scheduling a portfolio of projects competing for a limited pool of construction resources. The model uses five different types of data: resource availability, crew productivity, project scheduling, cost, and portfolio scheduling data, as shown in Figure 1. First, the user needs to provide data on the availability of resources in the contractor’s pool, including the types of resources used by the contractor, the number of available crews of each resource type, the availability dates of each crew, and the production rate adjustment factor for crews working overtime or night shifts. Second, for each of the resource types used by this contractor, the user also needs to input crew production rate data that is representative of the historical performance of each resource type. These data include selecting a suitable frequency distribution for crew production rate (i.e. beta, triangular, normal … etc.) and providing the statistical data required to describe the selected distribution (e.g. most likely, optimistic, and pessimistic production rates in the case of the beta distribution). The selected frequency distribution should be representative of the time-related risk factors that can significantly change crew production rate on shift-to-shift or day-to-day basis. Third, project schedule data include the planned activities for each project of the portfolio, scope of work (i.e. quantity) of each activity, resource requirements, and activity precedence information. Fourth, the user is required to provide data on direct and indirect costs. Direct costs include cost rates of each resource type and a lumpsum material cost for each activity. The indirect cost input data include one fixed daily rate for each project of the portfolio to cover site and main office overheads. Finally, the portfolio schedule data include projects prioritization (i.e. order of project execution), and working schedule and overtime policy for each project.

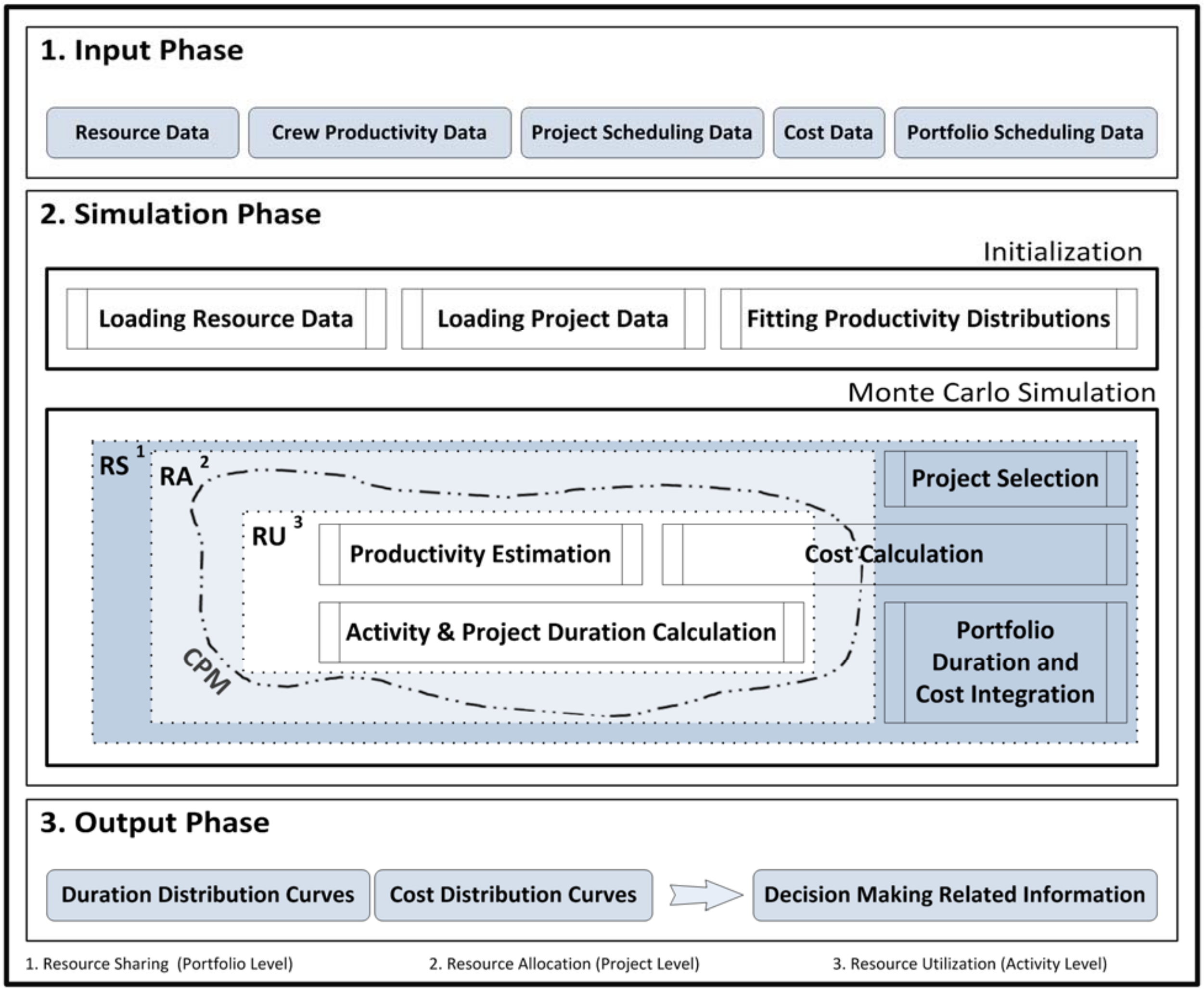

Figure 1. Productivity Simulation Model (PSM)

2.2 Simulation Phase

The main purpose of this phase of PSM is to simulate the productivity of the contractor's crews and analyze its impact on construction duration and cost at both the project and portfolio levels. This phase of PSM has two main procedures: initialization and Monte Carlo simulation.

Initialization Procedure is executed only once at the onset of running PSM and is aimed at loading the resource and project data collected in the previous phase and storing it in efficient data structures. These data structures are designed to provide swift access and seamless sharing of data among the different PSM processes in order to reduce the PSM computational overhead. Furthermore, the initialization procedure also includes fitting frequency distribution curves for crew production rate based on the crew data collected in the previous phase. This curve fitting process is completed for each crew in the contractor's resource pool based on the distribution curve selected by the user and the descriptive statistical productivity data provided in the input phase. Currently, PSM only considers beta distribution; therefore, any simulated instances of a crew's production rate should be generated using a Beta Probability Density Function (PDF). To this end, PSM generates the simulated crew production rate instances using the widely accepted Program Evaluation and Review Technique (PERT). Therefore, the mean and standard deviation of crew production rate can be estimated as follows:

[1]. $\mu_n = \frac{(P_{opt})_n + 4 \times (P_{ml})_n + (P_{pes})_n}{6}$

[2]. $\sigma_n = \frac{(P_{opt})_n - (P_{pes})_n}{6}$

Where, (μ_n) and (σ_n) are the mean and standard deviation of crew (n) production rate, respectively. $(P_{opt})_n$, $(P_{ml})_n$, and $(P_{pes})_n$ are the optimistic, most likely, and pessimistic production rates of crew (n), respectively; as collected from the user in the input phase. The estimated production rate mean and standard deviation are then used with an inverse beta function to generate the simulated instances of production rate that follows the beta probability density function. This process ensures generating crew productivities that are representative of the impact of time-related risk factors and their associated uncertainties.

Monte Carlo Simulation Procedure is the core of PSM and is comprised of several processes and methods that are designed to analyze and measure the impact of the aforementioned risk factors and their associated uncertainties on construction duration and cost at the project and portfolio levels. This is achieved by analyzing construction resource utilization and management practices based on the simulated crew production rate instances. To this end, PSM analyzes resource management at three main levels: resource utilization at the activity level; resource allocation at the project level; and resource sharing at the portfolio level, as shown in Figure 1. At the activity level, PSM analyzes the impact of the simulated production rate instances on activity durations and therefore costs, which accounts for the risk factors that can result in changing production rate on a day-to-day basis. At the project level, the estimated activity durations are used to allocate the limited construction resources available to different activities based on the resource requirements of these activities and the project logic. At the portfolio level, PSM analyzes the impact of sharing the limited resources among competing projects on the duration and cost of these projects according to the prioritization specified by the user. This procedure is executed for a number of iterations predefined by the user and involves two nested loops, as described in the following steps (see Figure 2):

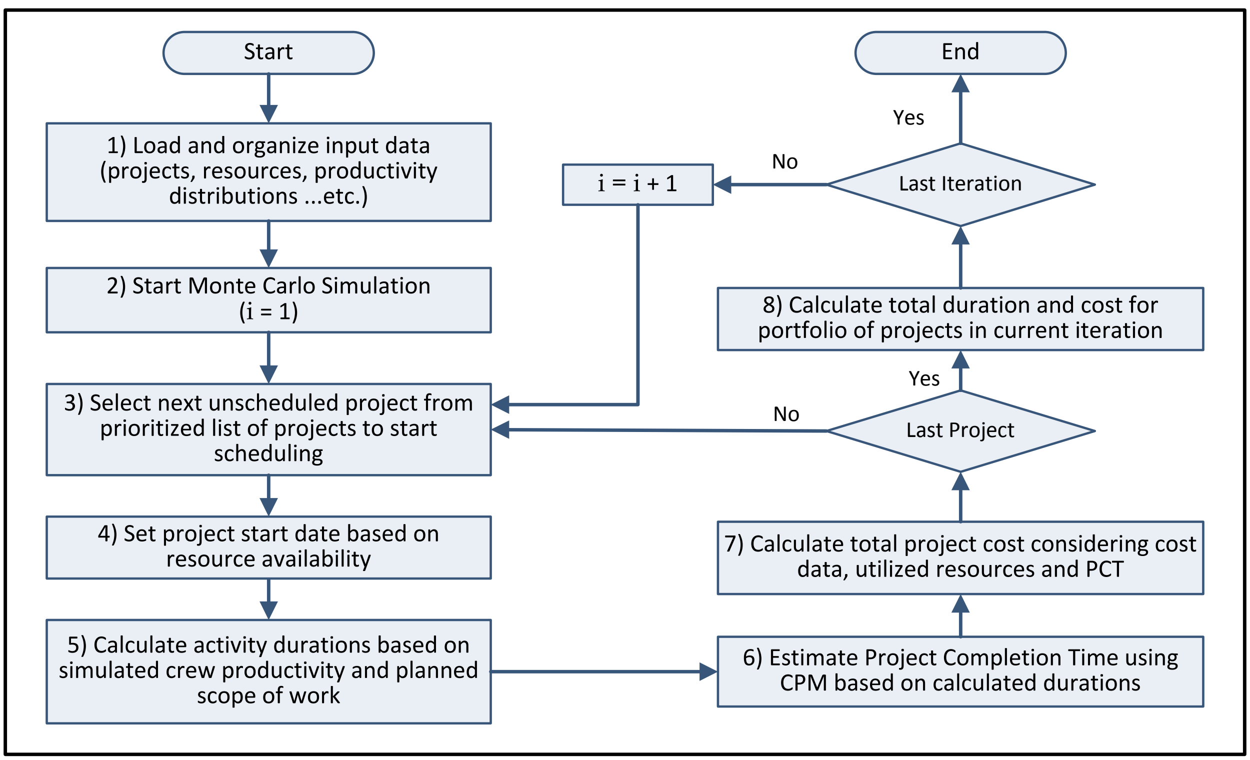

Figure 2. Flowchart for the Monte Carlo simulation procedure

1. Load project, resources and productivity data and store them in appropriate data structures, which allow swift and efficient access in the following steps.

2. Start the Monte Carlo simulation procedure and repeat it for a predefined number of iterations (i) set by the user. Therefore, the following steps 3 through 8 are repeated iteratively for (i) times.

3. Select the next unscheduled project (p) of the portfolio according to the project prioritization identified by the user. This is at the portfolio level resource management (i.e. resource sharing) and is designed to give projects with higher priority access to the contractor's limited resource pool before other projects that have lower priority.

4. Set the start date of the current project (p) based on the availability of resources. This data depends on having enough resources available and free to work on this project. Resources become free once they complete all work required on projects of higher priority and are released to the contractor's pool for use in other projects. The start date of the first activity of project (p), and accordingly the project start date, is therefore set to the early finish of the last activity using the same resource type in the immediately preceding project in terms of priority. PSM uses a resource-tracking database that is updated every time a crew is deployed to or from the resource pool to facilitate sharing construction crews at both the project and portfolio levels. This database can provide the number and types of resources available at any point in time. It is noteworthy that PSM allows activities to start with fewer crews than its requirements and can adjust the production rate as more crews become available.

5. Calculate the duration of all activities in the current project (p) based on the simulated instances of crew production rate. As mentioned in step 4, an activity can start with a fewer number of crews than required and its production rate gradually increases as more crews become available according to the resource-tracking database. The production rate of construction resources is therefore not constant over the duration of activity (a). Actually, two main factors contribute to the variability in production rate of construction resources over an activity's duration: the varying number of crews available; and the individual production rate of these crews that can change from one shift to the other due to time-related risk factors and the project overtime policy implemented, if any. PSM therefore uses a process to calculate project duration that takes into consideration this variable crew production rate. This process monitors the amount of work that can be completed during each shift and estimates how many time units (e.g. days) are needed to complete the entire work and hence the activity duration. This activity duration calculation process includes the following equations:

   [3]. $q_x = \sum_{s=1}^{n} p_x^s$

   [4]. $Q_r = Q_{total} - q_x$

   Where, (q_x) is the quantity of work that can be completed in day (x), (p_x^s) is the crew production rate in shift (s) of day (x), (n) is the number of working shifts according to the implemented overtime policy, (Q_r) is the remaining quantity of work at the end of each day, and (Q_{total}) is the total quantity of work required for activity (a). It is noteworthy that (p_x^s) takes into consideration adjusting the production rate for crew working for extended hours or second shifts due to the expected fatigue. Equations (3) and (4) are repeated iteratively until (Q_r) is equal to or less than zero. The minimum number of days needed to have (Q_r) equal to or less than zero is the duration of activity (a). As described above, crew production rate (p_x^s) is simulated to fit the beta probability density function using a random number that is generated individually for each single crew of each working shift (s).

6. Estimate the completion time of project (p) based on the activity durations calculated in the previous step and according to the planning project logic using the Critical Path Method (CPM). To this end, the start date of any activity (a) will depend on the completion of the immediately preceding

activities and availability of resources similar to setting project start date in step 4. This step is performed concurrently with step 5 by setting the start date of activity (a), calculating its duration, and setting its finish date before moving on to the following activity until all activities are scheduled and the project completion time (PCT) is set to be the earliest finish of the last activity.

7. Calculate the total cost of project (p), which is comprised of two main types of cost: direct (DC) and indirect (IC), as shown in Figure 3. In PSM, the direct cost includes the lumpsum cost of material required for completing the planned work, and the construction crew cost. The crew cost is estimated as the product of each activity's duration and the crew cost rate. Activity crew costs are then added up to calculate the total crew cost for the entire project. The indirect cost is estimated as the product of the project duration and the indirect cost rate that represents site and main office overheads. Steps 3 through 7 are repeated iteratively until all the projects of the portfolio are scheduled and their duration and total costs are known.

8. Calculate the duration and total cost for completing the portfolio based on the duration and cost of the individual projects as per steps 3 through 7. The portfolio duration is estimated as the difference between the latest early finish and earliest early start of all projects. The total portfolio cost however is the summation of all project costs. The estimated portfolio duration and cost in this step are associated only with the current iteration (i) and are dependent on the simulated crew production rate of the same iteration. Therefore, in order to account for the aforementioned time-related risk factors and their associated uncertainties, steps 3 through 8 are repeated for a predefined number of iterations, and storing the pairs of portfolio duration and cost of each iteration for further analysis.

2.3 Output Phase

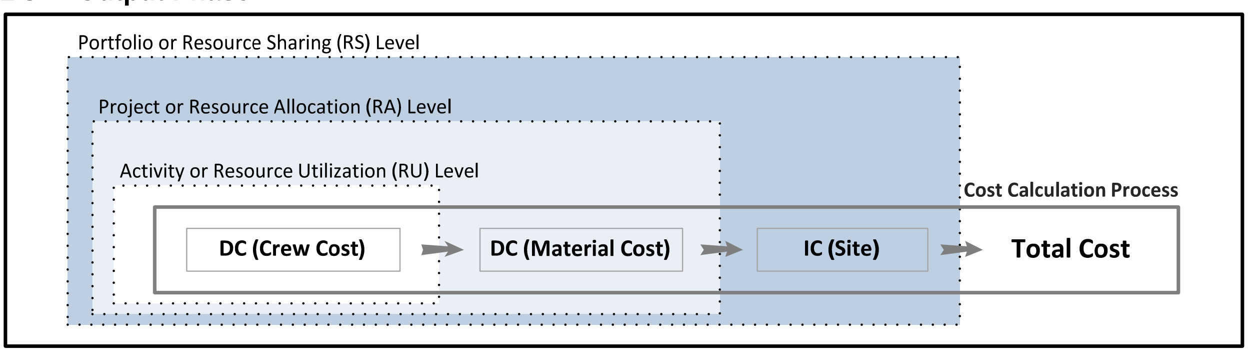

Figure 3. Construction cost calculation at the different resource utilization levels

The main purpose of this phase of PSM is to use the results of the simulation in order to help planners identify an estimate for portfolio duration and cost according to their risk tolerance. To this end, the pairs of portfolio duration and cost generated for each iteration of the simulation phase is used to develop frequency distribution curves for both portfolio duration and cost. These distribution curves depict the frequency of occurrence of each portfolio duration and each portfolio cost according to the simulated crew production rate. Similarly, each project can have distribution curves for its duration and cost that can be used for decision making at the project-level. Planners can therefore identify, at any of the portfolio or project levels, the duration and cost for a given confidence level, which is representative of their risk tolerance. Furthermore, these distribution curves can be used in further analyses, e.g. what-if scenarios, in order to identify an optimal utilization plan of the limited resource pool. The following section demonstrates an example of how to use PSM to plan and schedule construction projects.

3. Application Example

An application example for planning a portfolio of constructing three identical prefabricated metal buildings is analyzed to illustrate the use of PSM and demonstrate its capabilities. The activities in these three projects are similar and are adopted from Ahuja et al. (1995). Each project consists of five activities and requires five different types of construction resources. Table 1 shows the five activities of each project, activity precedence information, activity quantity of work, required resources, crew productivity data (i.e. optimistic, most likely, and pessimistic daily production rates), material and crew cost rates, and the number of crews available of each resource type. The daily indirect costs are $800, $850 and $1000 for projects 1, 2 and 3, respectively. In addition, the projects are numbered based on their priority. All three projects are assumed to work for two shifts per working day.

Table 1: Application example project and resource data

Sample Project Data					Available Resources Pool of the Portfolio							
Activity	Description	Predecessors	Quantity	Unit	Required Crew Type	Crew Daily Productivity			Material Unit Cost	Crew Daily Cost	Available Number of Crews
						Optimistic	Most Likely	Pessimistic			
1	Prefab metal building	none	60	Ton	A	0.30	0.27	0.24	185	850	3
2	Clear site	none	25,000	S.F.	B	500.00	208.33	166.67	0	1050	3
3	Underground and foundations	2	900	C.Y.	C	18.00	7.50	6.00	70	970	3
4	Erect prefab building	1,3	60	Ton	D	0.75	0.53	0.30	0	300	3
5	Finish interior	4	6,000	S.F.	E	66.67	59.70	54.55	100	740	3

This portfolio of projects was analyzed using the new PSM for a total number of 500 iterations. Figure 4 shows the resulting duration and cost distribution curves for each of the three projects and for the entire portfolio. Since the scope and resource requirements for all three projects are similar, their duration distribution curves are almost identical and ranges from 155 to 162 days for each project. The project cost distribution curves however, have similar shapes but different mean values due to the different indirect cost rates used for each project. At the portfolio level, the cost distribution curve shows total portfolio cost ranging from approximately $4,040,000 to over $4,080,000. Similarly, the portfolio duration distribution

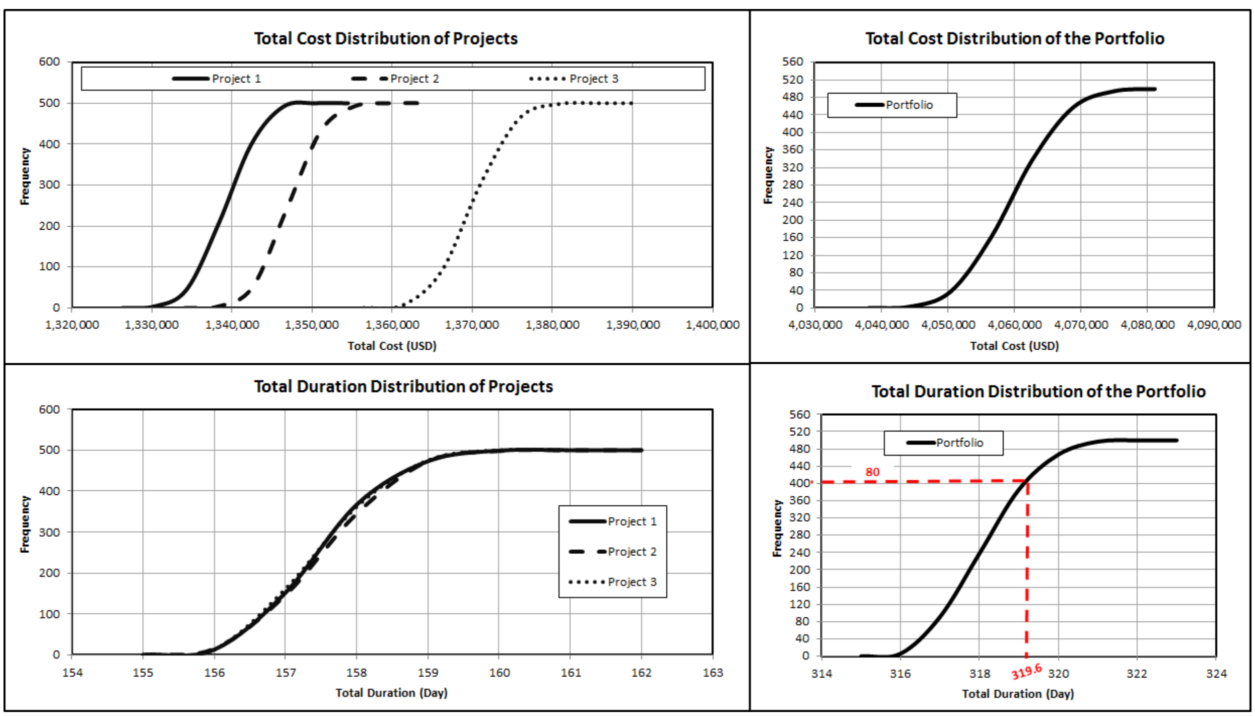

Figure 4. Duration and cost cumulative distribution curves at the project and portfolio levels

curve shows a total portfolio duration ranging between 315 and 323 days. Planners and decision makers can use these distribution curves to make informed bidding and resource utilization decisions that fit their needs and in accordance with their risk tolerance. For example, for a contractor bidding on a similar three-project portfolio, the estimator can safely assume that their an 80% probability the entire portfolio is expected to complete after 320 days or less. For other contractors who are more risk averse, they can select a higher probability (e.g. 95%) according to their risk utility, which will result in a higher duration, and vice versa for risk loving contractors who are willing to bear more risks and can select a lower probability.

4. Conclusions and Recommendations for Future Research

Construction projects are prone to myriad time-related risk factors (e.g. weather, labor availability, and trade coordination) that can result in significant changes in crew production rate on a day-to-day basis. This scheduling uncertainty problem makes it challenging for planners and decision makers to plan these projects and select optimal resource utilization plans. Existing stochastic planning models are insufficient to solve this problem since they depend on simulating activity and/or project duration, which does not address the problem of daily changes in crew production rate. Therefore, this paper presented the development of new productivity simulation model (PSM) that estimates activity, and hence project, durations based on simulated crew production rate. In addition, PSM is also capable of planning a portfolio of projects competing for a limited pool of resources and considers the impact of working for extended hours of multiple working shifts. The model is comprised of three main phases. First, the input phase collects project and resource data that are readily available for users. Second, the simulation phase uses Monte Carlo simulation to capture the variation in crew production rate and its impact on construction duration and cost at both the project and portfolio levels. Finally, the output phase provides the user with distribution curves for construction duration and cost, which allows planners to make informed decisions. PSM also uses three levels of resource management to facilitate effective and efficient resource utilization at the activity, project, and portfolio levels.

Further research is needed in order to improve the capabilities of PSM and provide more accurate depiction of construction risks and their impacts on different planning objectives. For example, the model could be expanded to consider the impact of risk factors on material costs and crew cost rates. In addition, resource utilization decisions can be optimized in order to select the project prioritization and overtime policy options that can simultaneously minimize portfolio construction duration and cost.

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