Integrating Schedule Risk Analysis with Multi-Skilled Resource Scheduling to Improve Resource-Constrained Project Scheduling Problems

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Abstract: Construction projects are planned in a complex and dynamic environment characterized by high risks and uncertainties amidst resource constraints. Assessing construction schedule risk facilitates informed decision-making, especially in a resource-constrained situation, and allows proactive actions to be taken so that project objectives are not jeopardized. This study presents a stochastic multiskilled resource scheduling (SMSRS) model for resource-constrained project scheduling problems (RCSPSP) considering the impact of risk and uncertainty on activity durations. The SMSRS model was developed by integrating a schedule risk analysis (SRA) model (developed in MS Excel) with an existing multiskilled resource scheduling (MSRS) algorithm for the development of a feasible and realistic schedule. The computational experiment carried out on three case projects using the proposed SMSRS model revealed an average percentage deviation of 10.50%, indicating the inherent risk and uncertainty in activity durations of the project schedule. The core contribution of the proposed SMSRS model is that it: (1) presents project practitioners with a simple tool for assessing the risks and uncertainty associated with resource-constrained project schedules so that necessary response actions can be taken to ensure project success; (2) provides the small-scale construction businesses with an affordable tool for evaluating schedule risk and developing a feasible and realistic project schedule.

Keywords: schedule risk analysis; risk; uncertainty; multiskilled resource scheduling; resource-constrained project scheduling problems; construction projects

1. Introduction

The construction industry is one of the mainstream industries that contribute to the growth of the global economy [1] through the implementation of construction projects ranging from small to mega projects. According to the 2015 report of the Global Construction 2030, the global spending on construction and engineering projects is expected to reach over $212 trillion by 2030 [2]. However, achieving the desired productivity and project success corresponding to the value of forecasted spending in the report hinges upon the effective management of project objectives (costs, time, scope, and quality) and the associated risk and uncertainty that influence the project outcome. Generally, the construction industry and business are characterized by high risk and uncertainties [3] due to the complexity and dynamism [1,4] involved in construction projects. A typical construction project consists of many activities that require a huge volume of resources (materials, equipment, labor, capital, etc.) for successful delivery. Nonetheless, these resources are limited in the project resource pool of any given project [5]. Hence, the project manager/planner is expected to plan the project by developing a feasible and realistic schedule considering risks, uncertainties and resource constraints.

Traditionally, the critical path method (CPM) has been a common tool used for the planning and coordination of construction activities. However, CPM is inadequate for
developing a schedule with realistic project durations [6] especially when dealing with a resource-constrained project. This is because the CPM schedule is based on optimistic activity durations and the assumption that resources are unlimitedly available which is unusual in a real project scenario [6–8].

Every construction project is prone to risk [8], uncertainty, and constrained with resources [9]. Thus, risk and uncertainty related to the project schedule must be assessed to enhance project success while ensuring the development of a time-resource-feasible schedule considering the resource constraints. Further, schedule risk analysis (SRA) and multiskilled resource scheduling (MSRS) are the strategies used to address schedule risk and resource constraints. On one hand, SRA involves linking the risk information of each activity of a project to the schedule baseline, in order to understand sensitivity information of each activity and to access the effect of uncertainty on the final project duration and cost [10]. On the other hand, MSRS is an extension of resource-constrained project scheduling problems (RCPSP) used as an optimization approach used for tackling the inefficiency of the single-skilled resource (SSR) scheduling strategy and to reduce project delay while utilizing scarce resources effectively to achieve project success.

Although, various tools, models, and methods used for carrying out SRA and MSRS have been developed and adopted by practitioners and researchers. For example, @Risk (at-risk) is a Monte Carlo simulation-based commercial software and an add-in to Microsoft Excel developed by Palisade used for cost and schedule risk analysis. However, the software focuses on determining realistic activity durations without considering resource constraints. Moreover, the cost of purchasing the software and training is too high to be affordable for small-scale firms, especially in developing countries. Additionally, among the numerous MSRS models that have been proposed in the literature, the heuristic algorithm for MSRS proposed by [11] remains the most applicable method for the scheduling of construction projects under resource-constrained due to its simplicity and explicit scheduling procedures. However, the schedule generated using the algorithm is based on a single point (deterministic) activity durations with no consideration for risk and uncertainty inherent in activity durations. Managing projects with such a schedule can lead to project slips. Looking at the high cost of the commercial software and the drawback in the existing MSRS algorithm there remains the need to provide an alternative and affordable tool for scheduling projects under resource constraints considering schedule risk in order to develop a construction schedule with reliable and realistic duration.

Consequently, this study aims to develop a stochastic MSRS (SMSRS) model for scheduling construction projects under resource constraints by integrating schedule risk analysis (SRA) with MSRS to improve RCPSP. In specific, we developed an SRA model using triangular distribution and Monte Carlo simulation aided with an MS Excel spreadsheet. The SRA model was then integrated with an existing heuristic MSRS algorithm by [11]. The proposed SMSRS model provides practitioners with a simple and affordable tool for developing an optimal, feasible, and realistic construction schedule that guarantees the timely completion of projects.

The remaining parts of the paper are organized as follows. Section 2 reviews relevant literature related to this study while Section 3 briefly explains the existing MSRS model. Section 4 explains the methodology of the proposed SMSRS model in detail with computational examples. Section 5 discusses the results of the computation examples while Section 6 presents the conclusion and future direction of the paper.

2. Literature Review
2.1. Schedule Risk Analysis (SRA)

Construction projects are not exempted from risk in that they are initiated in a complex and dynamic environment associated with high risk and uncertainty which is compounded by time [8] and resource constraints. Risk is defined as “an uncertain event or condition that, if it occurs, has a positive or a negative effect on project objectives” [9]. Risk management is an indispensable component of construction project management. Choudhry et al. [8]
stated that risk analysis is an important aspect of risk management that allows project practitioners to quantify and analyze the risk that may impact the performance of a project in terms of time, cost, quality, and safety. Equally, Akintoye and Macleod [12] affirmed that risk management is crucial to construction activities in reducing losses and maximizing profits. Additionally, Sanchez [13] stressed the need to integrate risk management into the organization’s culture as a safety measure against unforeseen events that might negatively impact organizational goals and project outcomes. SRA is a method used for analyzing the risk and uncertainty peculiar to the schedule baseline. Sackey and Kim [14] stipulated that SRA is conducted to assess the variability of the activity durations and to estimate the probability of completing the project within the project time.

Furthermore, to analyze risk several models, tools and techniques have been developed by practitioners and researchers [8,15,16]. The program evaluation and review technique (PERT) was the early SRA tool developed and used by the U.S. Department of the Navy in weapon system management [8]. Likewise, Nasir et al. [15] developed an SRA model called the evaluating risk in construction–schedule (ERIC-S) model for construction schedule risk analysis by determining the optimistic and pessimistic activity durations of schedule based on the project characteristics. Another SRA tool developed by [16] is the correlated schedule risk analysis model (CSRAM) use for evaluating the correlation between activity durations and risk factors to establish the degree of uncertainty in the schedule. Most of the aforementioned models are either CPM or PERT based model with their drawbacks. @Risk, Crystal ball, primavera risk analysis R8.x, etc. are the popular risk analysis software developed based on statistical method and Monte Carlo simulation. However, these tools have their limitations. @Risk for example can only deal with the risk and uncertainty that is related to scheduled activity durations but cannot resolve the issues that are related to resource conflict of resource-constrained projects. However, the software is still not affordable to most small-scale companies in the developing countries, especially when coupled with the time and cost required for the software training. Therefore, it is imperative to develop an alternative SRA tool that is simple, easy-to-use, and affordable to small-scale firms.

Triangular Probability Distribution

One of the objectives of this study is to develop an SRA model with the aid of a simple and accessible tool. Microsoft (MS) Excel is an application program accessible to all Microsoft Office users. MS Excel is a simple but powerful tool that is used as a platform upon which many commercial risk analysis software are built. This is due to various functions embedded in the spreadsheet, which can be used to perform different mathematical computations, statistical analysis, simulation, etc.

Usually, to conduct SRA in MS excel, different statistical probability distributions such as normal, beta, lognormal distributions, etc. are employed to generate stochastic activity durations. However, past studies have confirmed that triangular distribution is the most acceptable for SRA. Johnson [17] reported in a study, that the statisticians recommended triangular distribution as the best alternative to beta distribution because beta distribution maximum-likelihood parameters are not explicit enough. Similarly, Fairchild et al. [18] stated that triangular distribution is a preferred choice for many situations in that it gives a better estimate of variables under consideration even when the mean and standard deviation are not known. Further, the triangular distribution is a distribution based on three-point distribution with a lower limit (minimum or pessimistic), a modal (most likely), and an upper limit (maximum or optimistic) values. Researchers have adopted it in modeling real-world scenarios of uncertainties for project duration and budget. Yang [19] modeled budget uncertainty using normal, beta, and triangular distributions. The study concluded that triangular distribution performed better than both normal and beta probability distributions. Additionally, Back et al., Glickman and Xu [20,21]. stressed the usefulness of triangular distribution in the generation of random variables especially when parameters are gathered through subjective experts’ judgments. Consequently, the present
study adopted triangular probability distribution in the development of the SRA model with the aid of Microsoft Excel spreadsheet.

2.2. Multiskilled Resources Scheduling (MSRS)

Resource shortage and low productivity are two of the major challenges facing the construction industry [11,22]. Multiskilling is a resource utilization approach that has been identified as a promising strategy for addressing these two challenges [11,22,23]. A multiskilled resource is simply a worker who has more than one trade skill and competence to carry out multiple tasks of a project i.e., the ability of a plumber to carry out electrical work [11].

Many studies in the past have acknowledged the benefits of multiskilled resource strategy [23]. These benefits include but are not limited to an increment in earnings of the multiskilled workers, a 35% reduction in total labor requirement, 5–20% labor cost savings, and a 47% increase in average employment duration. Recently, Shang et al. [22] stipulated that improved safety onsite, improved project quality, flexible staff deployment, easing the shortfalls of skilled labor, improved job satisfaction, and improved competence of workers as additional benefits of implementing multiskilled resource strategy in the construction industry. Moreover, in the last five decades, these benefits had led to the continuous evolution of MSRS best practices through the development of various mathematical and heuristic scheduling models/algorithms by researchers and practitioners. Burleson et al. [23] developed an analytical model that was used to assess the impact of four multiskilling strategies on a construction project worth USD 70,000,000. The study noted that the multiskilling strategy could yield up to 20% labor cost savings among other benefits. In like manner, Gomar et al. [24] proposed a linear programming model for optimizing a multiskilled workforce thereby realizing up to 20% improvement in workforce performance. However, the authors stated that the application of the model is limited to the partial employment situation.

Furthermore, Hegazy et al. [11] introduced a heuristic multiskilled algorithm for scheduling resource-constrained projects using resource substitution rules. The algorithm utilizes resource information to resolving resource conflicts by substituting the under-allocated resources for the over-allocated ones based on predefined resource substitution rules and relative to the available multiskilled resources in the resource pool. In the same way, Wongwai and Malaikrisanachalee [25] presented an augmented algorithm for multiskilled resource scheduling based on the resource substitution approach and resource-driven activity duration. The author adopted vertical resource assignment to generate optimal and feasible resource schedules. In another study, Liu and Wang [26] introduced a constraint programming (CP-based) optimization model for generating an optimal schedule in linear projects involving complicated combinatorial scheduling problem based on the integration of single/multiskilled crews. Further, Li and Womer [27] developed a hybrid-benders decomposition (HBD) algorithm using mixed-integer linear programming (MILP) and constraint programming (CP). In the study, both MILP and CP’s strengths were combined to resolve the resource conflict of an assignment type of RCPSP leading to a minimized total staffing cost of multi-skilled personnel. Kazemipoor [28] examined a multiskilled project portfolio scheduling problem (MSPPSP) using a metaheuristic algorithm based on differential evolution (DE). The result revealed a minimized project duration deviation and efficient resource assignment for each project of the project portfolio.

Priority Rule (PR)

In MSRS, PR plays a significant role in the development of a feasible resource schedule. PR is a technique used in making decisions when dealing with a generic RCPSP. It is used to determine the order in which resources will be allocated to each activity during scheduling. Table 1 shows some of the popularly used PRs in MSRS. In their research, Hegazy et al. [11] applied the late start time (LST) priority rule to develop an optimal resource schedule with minimized delay. Additionally, Almeida et al. [29] used a multi-priority rule-based
concept to resolve a multi-skill RCPSP. In another study, Akpan [30] compared a case of random activity selection with the popularly used priority rules and suggested that the random activity selection rule produces an optimum solution than the other priority rules. In contrast, Browning and Yassine [31] argued that the performance of priority rules depends on project size, degree of resource contention, and resource distribution. Similarly, Elfiky et al. [32] established that no PR can be ranked best in different project circumstances and resource availability. Additionally, project practitioners and researchers have debated without a conclusive end on which PR is better in all project situations. Ultimately, the performance of the priority rule depends on the characteristics of the project such as project size, precedence relationships of the project activities, and availability of resource.

Table 1. Priority rules frequently used.

| Priority Rule Activity Listing Order | Activity Listing Order |
|-------------------------------------|------------------------|
| Shortest Activity Duration (SAD)    | Activities are listed in increasing order of SAD |
| Longest Activity Duration (LAD)     | Activities are listed in decreasing order of LAD |
| Earliest Start Time (EST)           | Activities are listed in increasing order of EST |
| Earliest Finish Time (EFT)          | Activities are listed in increasing order of EFT |
| Latest Start Time (LST) [11]        | Activities are listed in increasing order of LST |
| Latest Finish Time (LFT)           | Activities are listed in increasing order of LFT |
| Minimum Slack (MSLK)                | Activities are listed in increasing order of MSLK |

2.3. Stochastic Multiskilled Resources Scheduling (SMSRS)

Despite the contributions of the previous studies to MSRS, projects continue to deviate from the planned baselines. Sometimes, these deviations may result from several risk factors, which include but are not limited to underestimation of work content, error in the activity duration estimated, bad weather, delay supply of material, lack of substantial information at the early stage of the project, etc. [33]. Other situational risks that may constitute uncertainty in activity duration is the introduction of new technology, external regulations, and pressure from the client to complete the project earlier than the planned completion date. These risks and several assumptions (implicit or explicit) made during the development of the schedule called for robust resource scheduling. A robust resource schedule accounts for various risks and uncertainties that might influence the project delivery.

Numerous studies have proposed different SMSRS models. Ballestin and Leus [34] examined multi-objective functions for project scheduling with stochastic activity durations using a greedy randomized adaptive search procedure (GRASP) to minimize project makespan. It was established in the study that the stochastic models are better than the deterministic model. Lambrechts et al. [35] also investigated the impact of resource breakdown on activity duration focusing only on resource failure and repair times using a stochastic model. The study revealed that stochastic scheduling offers more advantage of providing a good time buffer to accommodate for variability in activity durations. Gutjahr [36] proposed a bi-objective multi-mode RCPSP model considering risk and uncertainty based on an analytical (mathematical) method. The model was used to generate random activity durations and cost estimates. Similarly, Li and Womer [37] applied a stochastic resource-constrained project schedule problem (SRCPSP) model to obtain a near-optimal solution for RCPSP based on a computationally tractable closed-loop approximate dynamic programming. Additionally, Felberbauer et al. [38] developed two stochastic optimization approaches for multi-skilled scheduling namely the metaheuristic and mixed-integer programming methods to address the uncertainty on work package processing times. External cost reduction was achieved in this study using external human resources to augment the shortage of internal human resources.
3. Existing MSRS Model

The existing MSRS models developed by [11,25] were improvements to the conventional single-skilled resource scheduling where activities are delayed when the daily resource requirement exceeds the available resources. The algorithm of Hegazy et al. [11] was adopted in this study due to the simplicity and easy scheduling procedure. The MSRS model uses resource substitution and heuristic priority rules to resolve resource conflicts thereby minimizing the project delay. Additionally, resource substitution was based on the assumption that workers have been cross-trained and certified to carry out multiple tasks. The substitution rules are formed based on project size, resource skill, and the available resources while the effectiveness of the rules depends on the ability of the project planner/manager to match the less utilized resources with the over-allocated ones. For example, the substitution rule 2R3 = 1R1 means two of resource R3 can replace resource R1 if there is a shortage of one resource R1 so that activity can either start or continue depending on the progress of the project.

Furthermore, in the development of the schedule using the MSRS model, first, the start and finish times of each activity and project duration are determined using the forward and backward pass method. Next, activities are listed for scheduling based on the desired priority rule (PR) to be adopted. Then, activities are scheduled using the adopted PR. In the process of scheduling, if resource conflict occurs, the multi-skill algorithm is applied based on the resource substitution rule to resolve the resource conflict so that activities are not delayed. However, if the substitution rule does not cover for the shortage of resources, then the activity is delayed until the next scheduling cycle. After scheduling all the activities, an optimal resource schedule with feasible project duration considering the resource constraints is developed while minimizing project delay.

Moreover, in the existing MSRS model, resource conflicts are resolved based on optimistic and deterministic activity durations without consideration for the risk and uncertainty that can impact scheduled activities. This limits the application of the model considering construction project realities. Hence, in the proposed stochastic MSRS (SMSRS) model, risk and uncertainty were incorporated into the model to generate a realistic schedule.

4. Materials and Methods

4.1. Proposed SMSRS Model

The proposed SMSRS model incorporates SRA with the MSRS algorithm of [11] to generate a resource schedule with a more realistic project completion duration. In the SMSRS model, we developed an SRA model with the aid of Microsoft excel using triangular probability distribution and Monte Carlo simulation. Thereafter, the SRA model was integrated with the MSRS algorithm.

Figure 1 shows an overview of the methodology for the existing MSRS and the proposed SMSRS models. To demonstrate the integration procedure, a sample project (project A) obtained from [11] was used to set up the model. Note that, the daily resource availability of the project was modified in order to formulate a suitable resource substitution rule adopted for the project. Figure 2 depicts the network diagram of project A, while Table 2 shows the project information which includes the activities, precedence relationships, activity durations, activity resource requirements, daily resources availability, and the resource substitution rule for the project. First, SRA was conducted to generate realistic activity durations. Then, the results obtained are used to conduct MSRS for the project so that realistic project completion time can be determined considering activity duration uncertainty.
so that realistic project completion time can be determined considering activity duration uncertainty.

Figure 1. Overview of research methodology.

![Figure 1. Overview of research methodology.](image)

Table 2. Project information for project A.

| Activity | Predecessor | Duration (Days) | Daily Resource Requirements |
|----------|-------------|----------------|------------------------------|
| A        | -           | 3              | R1 4, R2 4, R3 2            |
| B        | -           | 4              | R1 3, R2 4, R3 1            |
| C        | -           | 5              | R1 1, R2 3, R3 2            |
| D        | A           | 2              | R1 1, R2 0, R3 0            |
| E        | A           | 3              | R1 2, R2 1, R3 0            |
| F        | B           | 4              | R1 2, R2 2, R3 1            |
| G        | D,F         | 3              | R1 3, R2 1, R3 2            |
| H        | C           | 6              | R1 4, R2 4, R3 4            |
| I        | C           | 4              | R1 3, R2 2, R3 1            |
| J        | E,H         | 3              | R1 1, R2 4, R3 5            |

Daily Resources Availability: 7, 7, 10

Substitution rule: 2R3 = 1R1 and 2R3 = 1R2.

Figure 2. Network diagram for project A.

![Figure 2. Network diagram for project A.](image)
4.1.1. Development of SRA Model

SRA model was developed in MS excel following the steps below:

(i) Determine the optimistic \(a\), and pessimistic \(b\) durations of each activity duration

The optimistic \(a\), most likely \(m\) and pessimistic \(b\) durations for each activity were established. Note that, in the triangular probability distribution, \(a\), \(m\) and \(b\) values are required to generate random variables. Here, \(m_i\) is the given duration for each activity while \(a_i\) and \(b_i\) can be determined using expert judgment through survey, historical records, etc. However, in this study we determined \(a_i\) and \(b_i\) of each activity by multiplying \(m_i\) with fictitious values 0.8 and 1.5, respectively.

(ii) Generate random numbers between 0 and 1

Random numbers between 0 and 1 were generated using the excel function \(RAND()\) representing the probability occurrence of each variable.

(iii) Generate a random activity duration for each activity

Unlike other probability distributions whose random variables generating functions are available in excel, the triangular probability distribution function is not. Therefore, Equation (1) \([18]\) was used in MS excel to generate the random duration for each activity.

\[
Dur_{Rand_i} = IF\left( Rand_i \leq \frac{(m_i - a_i)}{(b_i - a_i)}, a_i + \sqrt{Rand_i \cdot (m_i - a_i) \cdot (b_i - a_i)} \cdot (b_i - \sqrt{(1 - Rand_i) \cdot (b_i - m_i) \cdot (b_i - a_i)}) \right)
\]  

where \(Rand_i\) is the random number generated for activity \(i\) and \(Dur_{Rand_i}\) is the random duration for activity \(i\).

(iv) Run Monte Carlo simulation for each activity duration

Each random activity duration generated was simulated 1000 times using the Monte Carlo simulation method. The average of 1000 iterations for each activity was calculated, which is the expected duration for each activity. Each time F9 is pressed on the keyboard, a new set of random durations are generated. In this way, the risk and uncertainty which may affect the activity durations were accounted for. The resultant expected activity durations (stochastic) were used as input for the development of the stochastic multi-skilled resource schedule. The results of these procedures are shown in Table 3.

Table 3. Results of SRA for project A.

| Activity | Pred. | \(a\) | \(m\) | \(b\) | \(Rand\) (0–1) | Random Duration | Average Duration | Distribution |
|----------|-------|-------|-------|-------|----------------|-----------------|-----------------|-------------|
| A        | -     | 2     | 3     | 5     | 0.25           | 2.86            | 3.31            | Triangular   |
| B        | -     | 3     | 4     | 6     | 0.07           | 3.44            | 4.27            | Triangular   |
| C        | -     | 4     | 5     | 8     | 0.68           | 6.05            | 5.71            | Triangular   |
| D        | A     | 1     | 2     | 3     | 0.24           | 1.69            | 1.93            | Triangular   |
| E        | A     | 2     | 3     | 5     | 0.76           | 3.81            | 3.32            | Triangular   |
| F        | B     | 3     | 4     | 6     | 0.97           | 5.54            | 4.33            | Triangular   |
| G        | D,F   | 2     | 3     | 5     | 0.55           | 3.29            | 3.28            | Triangular   |
| H        | C     | 5     | 6     | 9     | 0.01           | 5.24            | 6.65            | Triangular   |
| I        | C     | 3     | 4     | 6     | 0.38           | 4.07            | 4.32            | Triangular   |
| J        | E,H   | 2     | 3     | 5     | 0.62           | 3.36            | 3.33            | Triangular   |

4.1.2. Integrating the SRA Model with MSRS

This section explains the integration of the SRA model with the MSRS algorithm. To integrate the SRA with the MSRS algorithm, the stochastic activity durations obtained from the SRA model were used as input for the computational steps involved in the integration as described below:

(i) Determine project duration, start and finish times of each activity
The project duration, start and finish times based on the stochastic durations of each activity were computed using the forward and backward pass approach with the aid of Microsoft Excel using Equations (2a)–(2d). The result is shown in Table 4.

Table 4. Results of the forward and backward pass for the stochastic durations.

| Activity | Pred. | Duration | EST | EFT | LST | LFT | Slack |
|----------|-------|----------|-----|-----|-----|-----|-------|
| A        | -     | 3.31     | 0   | 3.31| 5.73| 9.04| 5.73  |
| B        | -     | 4.27     | 0   | 4.27| 3.81| 8.08| 3.81  |
| C        | -     | 5.71     | 0   | 5.71| 0   | 5.71| 0     |
| D        | A     | 1.93     | 3.31| 5.24| 10.48| 12.41| 7.17  |
| E        | A     | 3.32     | 3.31| 6.63| 9.04| 12.36| 5.73  |
| F        | B     | 4.33     | 4.27| 8.6 | 8.08| 12.41| 3.81  |
| G        | D,F   | 3.28     | 8.6 | 11.88| 12.41| 15.69| 3.81  |
| H        | C     | 6.65     | 5.71| 12.36| 5.71| 12.36| 0     |
| I        | C     | 4.32     | 5.71| 10.03| 11.37| 15.69| 5.66  |
| J        | E,H   | 3.33     | 12.36| 15.69| 12.36| 15.69| 0     |

\[
\text{EST}_i = \text{MAX} \left( \text{IF} \left( \text{ISERR} \left( \text{FIND} \left( \text{activity range}, 1\text{st pred.}\ i \right) \right), 0, \text{EFT range} \right) \right) \quad (2a)
\]

\[
\text{EFT}_i = \text{EST}_i + \text{Duration}_i \quad (2b)
\]

\[
\text{LFT}_i = \text{MIN} \left( \text{IF} \left( \text{ISERR} \left( \text{FIND} \left( 1\text{st activity, pred. range} \right) \right), \text{MAX} \left( \text{EFT range} \right), \text{LST range} \right) \right) \quad (2c)
\]

\[
\text{LST}_i = \text{LFT}_i - \text{Duration}_i \quad (2d)
\]

where Pred., EST, EFT, LST, and LFT are predecessor, early start time, early finish time, late start time, and late finish time of each activity.

(ii) Schedule each activity

Each activity was scheduled accordingly using the stochastic activity durations. MSRS algorithm was adopted at the instances of resource conflicts based on the resource substitution rule of the project in Table 2. After scheduling all the activities considering the resource constraints the project duration was 19.49 days as shown in Table 5. This duration is the expected project duration considering risk and uncertainty and resource constraints.

Table 5. Stochastic multi-skilled resource schedule (SMSRS) for Project A.

| Time | Eligible Activity | R1 = 7 | R2 = 7 | R3 = 10 | Duration (Day) | LAD | Decision | Full Time | Substitution Rule |
|------|------------------|--------|--------|---------|----------------|-----|----------|-----------|------------------|
| 0    | C                | 1      | 3      | 2       | 5.71           | 5.71| S        | 5.71     |                  |
|      | B                | 3      | 4      | 1       | 4.27           | 4.27| S        | 4.27     |                  |
|      | A                | 4      | 4      | 2       | 3.31           | 3.31| D        |          |                  |
| 4.27 | C                | 1      | 3      | 2       | 5.71           | -   | C        | 5.71     | 2R3 = 1R2       |
|      | F                | 2      | 2      | 1       | 4.33           | 4.33| S        | 8.6      | 2R3 = 1R1       |
|      | A                | 4      | 4      | 2       | 3.31           | -   | C        | 7.58     | 2R3 = 1R1       |
| 5.71 | F                | 2      | 2      | 1       | 4.33           | -   | C        | 8.6      |                  |
|      | A                | 4      | 4      | 2       | 3.31           | -   | C        | 7.58     |                  |
|      | H                | 4      | 4      | 4       | 6.65           | 6.65| D        |          | 2R3 = 1R2       |
|      | I                | 3 − 2  | 2 − 1  | 1 + 4 + 2| 4.32           | 4.32| S        | 10.03    |                  |
| 7.58 | F                | 2      | 2      | 1       | 4.33           | -   | C        | 8.6      |                  |
|      | I                | 3      | 2      | 1       | 4.32           | -   | C        | 10.03    |                  |
|      | H                | 4      | 4      | 4       | 6.65           | 6.65| D        |          |                  |
|      | E                | 2      | 1      | 0       | 3.32           | 3.32| S        | 11.17    | 2R3 = 1R1       |
|      | D                | 1 − 1  | 0      | 0 + 2   | 1.93           | 1.93| S        | 9.51     |                  |
Table 5. Cont.

| Time  | Eligible Activity | R1 = 7 | R2 = 7 | R3 = 10 | Duration (Day) | LAD | Decision | Full Time | Substitution Rule |
|-------|-------------------|--------|--------|---------|----------------|-----|----------|-----------|-------------------|
| 8.6   | I                 | 3      | 2      | 1       | 4.32           | -   | C        | 10.03     |                  |
|       | E                 | 2      | 1      | 0       | 3.32           | -   | C        | 11.17     |                  |
|       | D                 | 1      | 0      | 0       | 1.93           | -   | C        | 9.51      |                  |
|       | H                 | 4      | 4      | 4       | 6.65           | 6.65| D        | -         |                  |
| 9.51  | I                 | 3      | 2      | 1       | 4.32           | 4.32| C        | 10.03     |                  |
|       | E                 | 2      | 1      | 0       | 3.32           | -   | C        | 11.17     |                  |
|       | H                 | 4−2    | 4      | 4+4     | 6.65           | 6.65| S        | 16.16     | 2R3 = 1R1       |
|       | G                 | 3      | 1      | 2       | 3.28           | 3.28| D        | -         | 2R3 = 1R1       |
| 10.03 | E                 | 2      | 1      | 0       | 3.32           | -   | C        | 11.17     |                  |
|       | H                 | 4      | 4      | 4       | 6.65           | -   | C        | 16.16     |                  |
|       | G                 | 3−2    | 1      | 2+4     | 3.28           | 3.28| S        | 13.31     | 2R3 = 1R1       |
| 11.17 | H                 | 4      | 4      | 4       | 6.65           | -   | C        | 16.16     |                  |
|       | G                 | 3      | 1      | 2       | 3.28           | -   | C        | 13.31     |                  |
| 13.31 | H                 | 4      | 4      | 4       | 6.65           | -   | C        | 16.16     |                  |
| 16.16 | J                 | 1      | 4      | 5       | 3.33           | 3.33| S        | 19.49     |                  |

Legend: R1–R3 = resources, S = start; C = continue and D = delay; LAD = longest activity duration.

4.2. Scheduling Procedure

Table 5 shows the details of the scheduling. In this schedule, the longest activity duration (LAD) PR was used for the scheduling based on the project information in Table 2; Table 4. In Table 5, Column 1 (from the left) shows the starting time of the eligible activities while column 9 shows the corresponding finish times of the activities in each scheduling cycle. Column 2 shows the eligible activities while columns 3, 4, and 5 show the resources and the availability per day. The activity durations, the PR applied and the decision made in each cycle is shown in columns 6, 7, and 8, respectively. The last column shows the substitution rule used to resolve the resource shortage.

In the first cycle, i.e., at the beginning of the project (time = 0) as shown in Table 5 only activities C, B, and A were eligible and enlisted for scheduling. The activities were sorted base on LAD. Activities C and B were scheduled to be completed on days 5.71 and 4.27, respectively. Activity A was delayed because of insufficient resources and the substitution rule could not resolve the resource shortages for R1 and R2.

Then, in the second cycle (time = 4.27), activity B has been completed while activity C continued as scheduled in the previous cycle. The completion of activity B consequently made activity F eligible for scheduling in this cycle. Activity F and A were started accordingly and to be completed on days 8.6 and 7.58, respectively. Activity A was started by applying the resource substitution rule 2R3 = 1R2 in columns 4 and 5. The total R2 required by activities C, F, and A start is 9 of R2 which is 2 units above the daily availability (7 units). Therefore, 2 units of R2 were subtracted from column 4, and a corresponding 4 units of R3 were added in column 5. This way activity A was scheduled. Note that at the end of each cycle, the number of resources used by the activities either in starting or in progress should not exceed the availability per day of each resource. Additionally, notice that the start times for the next cycle is the earliest finished time of the previously scheduled activities. For example, in the 2nd cycle, the finish times for activities C, F, and A are 5.71, 8.6, and 7.58, respectively. Thus, the next cycle starts on day 5.71.

In the third cycle (time = 5.71), activity C was completed thereby making activities H and I eligible. Activities F and A continued as scheduled in the last cycle while activity H was delayed until the next cycle because resources were not enough to start them and the substitution rule could not resolve the resource conflict of R1 and R2. Thus, activity I started and to be finished on day 10.03 using the substitution rules 2R3 = 1R1 and 2R3 = 1R2. The shortage in R1 (2 units) and R2 (1 unit) in columns 3 and 4, respectively, were resolved in
column 5 (6 units of R3), so activity I was started. This scheduling procedure was continued till the last activity was scheduled resulting in a project duration of 19.49 days.

Similarly, two case projects obtained from literature namely; projects B [11,39] and C [25] were analyzed using the SMSRS model, and results were obtained. The project information and the network diagram are shown in Table 6; Table 7 and Figure 3; Figure 4 respectively. Additionally, the substitution rules adopted for these projects are shown in Table 6; Table 7 while PR used in scheduling was LST. We applied the LST rule to have an unbiased basis for comparison with existing studies where the two projects (A and B) were studied.

Table 6. Project information for Project B.

| Activity | Predecessors | Duration (Days) | R1 | R2 | R3 | R4 | R5 | R6 |
|----------|--------------|----------------|-----|----|----|----|----|----|
| A        | -            | 6              | 5   | 2  | 2  | 2  | 7  | 4  |
| B        | -            | 3              | 3   | 5  | 2  | 3  | 9  | 6  |
| C        | A            | 4              | 2   | 4  | 4  | 2  | 3  | 1  |
| D        | -            | 6              | 5   | 4  | 3  | 5  | 5  | 4  |
| E        | A,B          | 7              | 3   | 5  | 2  | 3  | 8  | 0  |
| F        | C            | 5              | 4   | 1  | 4  | 9  | 2  | 5  |
| G        | D            | 2              | 4   | 1  | 4  | 3  | 9  | 8  |
| H        | A,B          | 2              | 5   | 5  | 4  | 0  | 9  | 1  |
| I        | G,H          | 2              | 3   | 2  | 4  | 3  | 4  | 2  |
| J        | F            | 6              | 1   | 5  | 4  | 6  | 7  | 3  |
| K        | C,E          | 1              | 3   | 3  | 2  | 4  | 5  | 1  |
| L        | E,G,H        | 2              | 3   | 2  | 2  | 8  | 3  | 4  |
| M        | I,K          | 4              | 2   | 2  | 2  | 4  | 8  |    |
| N        | F,L          | 2              | 1   | 4  | 4  | 3  | 4  | 1  |
| O        | L            | 3              | 5   | 5  | 4  | 6  | 2  | 3  |
| P        | J,M,N        | 5              | 3   | 2  | 3  | 4  | 7  | 8  |
| Q        | O            | 8              | 4   | 5  | 4  | 2  | 3  | 4  |
| R        | D,O          | 2              | 5   | 3  | 3  | 3  | 7  | 8  |
| S        | P,R          | 6              | 2   | 4  | 6  | 2  | 3  | 4  |
| T        | Q            | 2              | 1   | 6  | 2  | 7  | 5  | 2  |

Daily resource availability 7 10 10 16 18 13

Substitution rule: 2R5 = 1R1; 2R4 = 1R2; 2R5 = 1R4; 2R4 = 1R5; 2R6 = 1R8.

FIGURE 3. Network Diagram for Project B.
Table 7. Project information for Project C.

| Activity | Predecessors | Duration (Days) | R1 | R2 | R3 | R4 | R5 |
|----------|--------------|-----------------|----|----|----|----|----|
| A        | -            | 8               | 1  | 3  | 2  | 1  | 2  |
| B        | -            | 9               | 5  | 4  | 2  | 1  | 2  |
| C        | -            | 6               | 0  | 1  | 1  | 1  | 2  |
| D        | -            | 7               | 4  | 2  | 3  | 1  | 4  |
| E        | A,B          | 11              | 1  | 2  | 1  | 1  | 2  |
| F        | A,B,C        | 13              | 1  | 4  | 1  | 1  | 0  |
| G        | B,C,D        | 10              | 1  | 6  | 1  | 1  | 5  |
| H        | C,D          | 14              | 7  | 1  | 1  | 2  | 3  |
| I        | E,F,G        | 12              | 1  | 2  | 1  | 1  | 2  |
| J        | E,F,G,H      | 13              | 1  | 2  | 2  | 1  | 3  |
| K        | G,H          | 12              | 7  | 7  | 3  | 2  | 4  |
| L        | I,J          | 13              | 1  | 2  | 2  | 2  | 1  |
| M        | I,J,K        | 15              | 5  | 4  | 1  | 2  | 2  |
| N        | J,K          | 14              | 4  | 3  | 1  | 3  | 4  |
| O        | L,M,N        | 14              | 2  | 3  | 2  | 2  | 3  |
| P        | L,M,N        | 15              | 5  | 4  | 2  | 3  | 6  |
| Q        | O,P          | 5               | 3  | 2  | 5  | 4  | 2  |

Daily resource availability 7 12 12 16 9

Substitution rule: 2R2 = 1R5, 2R2 = 1R1, 3R3 = 1R1 and 2R4 = 1R3.

Figure 4. Network Diagram for Project C.

Then, the SMSRS model results were validated through a comparison with results obtained from single-skilled resource scheduling (SSRS) software (RESCON) and the existing deterministic MSRS model. RESCON is a resource-constrained scheduling educational software based on a single-skilled resource strategy. Table 8 shows the schedule summary results of the three projects based on SSRS software, MSRS, and SMSRS models. Next, the project delay and percentage delay for the projects were computed using Equation (3). The results are shown in Table 9; Table 10 with the summary depicted in Figure 5. Finally, the average percentage delay error for the three projects was computed as 10.50%.

\[
\%D_i = \frac{P_i - P_B}{P_B} \times 100\%
\]  

(3)

where \(\%D_i\) is the percentage delay of schedule \(i\); \(P_i\) is the project duration for schedule \(i\) and \(P_B\) is the baseline project duration i.e., deterministic project duration.
Table 8. Schedule summary.

| Project | Baseline | SSRS | MSRS | SMSRS |
|---------|----------|------|------|-------|
| A       | 14       | 20   | 18   | 19.49 |
| B       | 32       | 49   | 35   | 38.12 |
| C       | 70       | 120  | 78   | 85.77 |

Table 9. Project delay summary.

| Project | Baseline | SSRS | MSRS | SMSRS |
|---------|----------|------|------|-------|
| A       | 14       | 6    | 4    | 5.49  |
| B       | 32       | 17   | 3    | 6.12  |
| C       | 70       | 50   | 8    | 15.77 |

Table 10. Percentage delay.

| Project | Baseline | MSRS | % Delay | SMSRS | % Delay |
|---------|----------|------|---------|-------|---------|
| A       | 14       | 4    | 28.57   | 5.49  | 39.21   |
| B       | 32       | 3    | 9.38    | 6.12  | 19.13   |
| C       | 70       | 8    | 11.43   | 15.77 | 22.53   |

Figure 5. Percentage delay error.

5. Discussion of the Results

This section discusses the results obtained from the computational examples carried out in Section 4 above. In Table 8, the baseline durations for projects A, B, and C are 14 days, 32 days, and 70 days, respectively, representing the project durations with no resource constraints. When we scheduled the projects using single-skilled resource scheduling (SSRS) software RESCON, the project durations increased to 20 days, 49 days, and 120 days for projects A, B, and C, respectively. However, using the existing MSRS model considering resource constraints, the project durations for projects A, B, and C were reduced to 18 days, 35 days, and 78 days for projects A, B, and C, respectively. These values correspond with the solution obtained in the previous studies. More so, considering risk and uncertainty using the SMSRS model, the optimized SMSRS durations became 19.49 days, 38.12 days, and 85.77 days for projects A, B, and C, respectively, which represent the expected project durations.

Additionally, from Table 9 it can be observed that both MSRS and SMSRS project delays are less compare to the SSRS duration. But, when the SMSRS schedule is compared with the existing MSRS result the difference of 1.49 days for project A, 3.12 days for project
B and 7.77 days for project C were observed revealing the extent of underestimation (uncertainty) of the existing MSRS model. These values indicate the impact of risk and uncertainty on the existing MSRS model. The impact can be higher depending on project type and size.

Likewise, in Table 10, we compared the results of percentage delays (deviations) obtained from both the MSRS and SMRS models with the schedule baseline. For MSRS, the percentage delay for projects A, B, and C is 28.57%, 9.38%, and 11.43%, respectively. These values indicate the amount of deviation of the project baseline schedule considering risk and uncertainty associated with activity duration and resource constraint. As for SMSRS, the percentage delay is 39.21% for project A, 19.13% for project B, and 22.53% for project C indicating the amount of deviation of project baseline from the SMSRS based on stochastic activity duration. Note that the values obtained from the SMSRS model are the expected percentage delay for each project taken into account risk and uncertainty. Figure 5 shows the percentage delay error for the projects. Project A is 10.64%, while projects B and C are 9.75% and 11.10%, respectively. The average percentage error for all three projects is 10.50%. This value points out the error in the estimation of project delay using the existing MSRS model. Therefore, based on these results the proposed SMSRS model offers a more realistic resource schedule with a minimized expected delay.

6. Conclusions

This study introduced a stochastic multiskilled resource scheduling (SMSRS) model for scheduling construction projects under resource constraints considering the impact of risk and uncertainty on activity durations. The SMSRS model was developed by integrating a schedule risk analysis (SRA) model with an existing MSRS algorithm. The SRA model is a simulated-based model that was developed using triangular probability distribution and Monte Carlo simulation with the aid of MS Excel for evaluating the risk and uncertainty inherent in construction activity durations. The resultant stochastic activity durations from the model were used to develop construction schedules with realistic duration using the MSRS algorithm. Additionally, the computational experiment of three projects carried out using the SMSRS model revealed an average deviation of 10.50% in the project duration, indicating the impact of risk and uncertainty on activity durations of the schedule.

The core contribution of the SMRS model to the body of knowledge is that it enables the project practitioner to evaluate the risk associated with a construction schedule under resource constraint and to determine the realistic schedule duration, thus facilitating informed and proactive decision-making while ensuring that projects are delivered on time and budget. In addition, the SMSRS model will be a valuable tool to the small-scale firms who cannot afford the expensive RCPSP software in:

1. Estimating accurate activity duration considering the effect of unforeseen events on project outcome;
2. Adequate estimation of the cost of the required resources of project task while preventing the project from cost overrun;
3. Improving activity coordination by experienced multiskilled workers based on the feasible project schedule while ensuring worker safety on-site; and
4. Revolutionizing the site process, adoption of technology, new labor strategy development, improve quality, and client requirement satisfaction.

Furthermore, in the analysis and scheduling carried out with the SMRS model, small projects limited to only 10–20 activities were examined. Hence, the extension of its application to real mega resource-constrained projects with more than 20 activities is a promising direction for future research. Moreover, to achieve more accurate activity duration simulation, more than 1000 iterations are recommended for the activities of complex projects coupled with the use of a high-speed computer to make activity duration simulation faster. Finally, to reduce computation and scheduling times in case of a mega-scale project, the authors look forward to automating the scheduling procedure using MS excel VBA or a
combination of MS excel with programming languages such as PYTHON and MATLAB in the nearest future.

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