Agent-Based Modeling and Simulation of Project Schedule Risk Analysis in the Construction Industry

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Abstract The risk of project delay is a common phenomenon with an adverse effect on the performance of projects in the construction sector. The effect of its negative impacts in terms of cost overruns, reduced quality, and productivity extends to the owner, consultant, and contractor. The goal of this paper is to introduce an agent-based simulation model for the risk analysis of the project schedule component of construction projects, based on three risk management decisions. In the simulated model, the authors indicate four main phases in the construction process, along with their approval stages: (1) handing over; (2) engineering; (3) procurement; and (4) construction, which are commonly subjected to delays in the completion of the required activities. In addition, the developed simulation model should allow decision-makers to explore the impact of risks on the project schedule, in terms of schedule and cost overrun, based on two risk-response controls: acceptance or mitigation. As such, three simulation models are formulated: (A) no risks; (B) with risks; and (C) with mitigation. The model has been run based on a 70% mitigation value. The results indicate rational values. Since the duration for the risks for the 'with risk' scenario resulted in the highest time, followed by the 'with mitigation' scenario, the lowest time is recorded for the 'no risks'. Similarly, the highest cost is recorded for the 'with mitigation' scenario, followed by the 'with risks', ending with the 'no risks' scenario. Further validation tools signified the effectiveness of the mitigation decision on the recorded results. This is demonstrated by the sudden drop as the mitigation value has been decreased based on the user's input.

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1 Introduction

Projects within the construction sector are associated with a high degree of risk and uncertainty [17]. Project risk is defined by International Standards as a 'combination of the probability of an event occurring and its consequences for project objectives' [19], whereas the Project Management Institute (PMI) discusses the concept of risk in more detail and raises the concept of uncertainty and the perception of risk as a negative event, in its definition of risk as 'an uncertain event of condition that, if it occurs, has a positive or negative effect on one or more project objectives' [26]. The risk of project delay is a common phenomenon with an adverse effect on the performance of projects in the construction sector [5, 29]. Construction project risks impact approximately 56% of projects, at varying extents [8]. Its negative impacts in terms of cost overruns, reduced quality, and productivity [35] lead to issues of litigations, disputes, and arbitrations, as its effect extends to the owner, consultant, and contractor [4]. Moreover, the impact of poor management and analysis of construction risks extends to affect the country's GDP [13].

The rapid increase in the size and level of complexity of projects in the construction industry increases the likelihoods and associated effects of project risks and uncertainties [17]. Thompson and Perry conclude that the lack of an effective risk management system is directly related to the failure of construction projects [33]. The literature pertaining to risk management systems focuses on the significance of identifying risk factors, analyzing their probability of occurrence and resultant impact, to reduce the probability and severity of risks on the attainment of project objectives [1, 28]. Moreover, the effective management of a project involves the efficient allocation of resources in each project phase, which would otherwise incur schedule and cost overruns [27]. Productivity in the construction sector has been at a considerable decline through the past years [6]. As such, risk management techniques are essential to an effective construction management process [30], as risks, resources allocation, and improvement of production productivity performance can be managed more proactively [31]. The purpose of this paper is to introduce an agent-based simulation model for the risk analysis of the project schedule component of construction projects. The developed simulation model should allow decision-makers to explore the impact of risks on the project schedule, in terms of schedule and cost overrun, based on two risk-response controls: acceptance or mitigation.

2 Research Background

This section first reviews current studies regarding the importance of the effective risk management in the construction industry and the attributed different phases and variables. Subsequently, it discusses the use of the Monte Caro simulation in assessing construction project risks. The section then concludes with an introduction to the basic principles of agent-based simulation modeling.

2.1 Risk Management in the Construction Industry

The successful delivery of construction projects is defined by the intrinsic relationship between the ability to meet the assigned project schedule within the budgeted amount and at the proposed quality [11]. In Egypt, thirty-seven percent of projects do not meet their cost constraints, as unexpected, incurred costs arise. In addition, ninety-eight percent of contractors fall behind the planned project time schedule [12]. The assessment of risk factors should be performed in the context of risk management. In their study, Ha et al. [17] express the value of risk factors (RV) by the below equation, governed by four variables (RV, P, I, and D). The four variables are defined over the range of 1–5, with RV over the range of 1–125. Yet the range values can be adjusted according to each construction project requirements and context [17].

$$\mathrm{RV} = P \times I \times D,$$

- ***P*** referred to as the probability of the risk occurrence.
- ***I*** referred to as the level of risk impact on project schedule and project objectives.
- ***D*** indicates the difficulty of the risk detection, control, and management process.

Project risk management is the formal, systematic process of identifying, assessing, and responding to any arising risks. There are different definitions and number of steps for the risk management process across the literature. The PMI [26] categorizes four main steps: (1) identification, (2) assessment,(3) response; and (4) management. Yet more comprehensive models are developed, Baloi and Price [9] propose a seven-step risk management model: (1) planning, (2) identification,(3) assessment; (4) analysis; (5) response; (6) monitoring; and (7) communication. The authors propose a five-step risk management process, illustrated in Fig. 1.

Literature reveals that delays in construction projects vary across different countries [14, 18, 23]. This is due to different variables such as construction environment, location, design requirements, and laborer's levels of expertise [20]. The most contributing factors of delay risks in construction projects in Egypt could be categorized into nine categories: (1) consultant-related,(2) contractor-related,(3) design-related; (4) equipment-related; (5) external-related; (6) labor-related; (7) material-related; (8) client-related; and (9) project-related [7, 24]. In the simulated model,

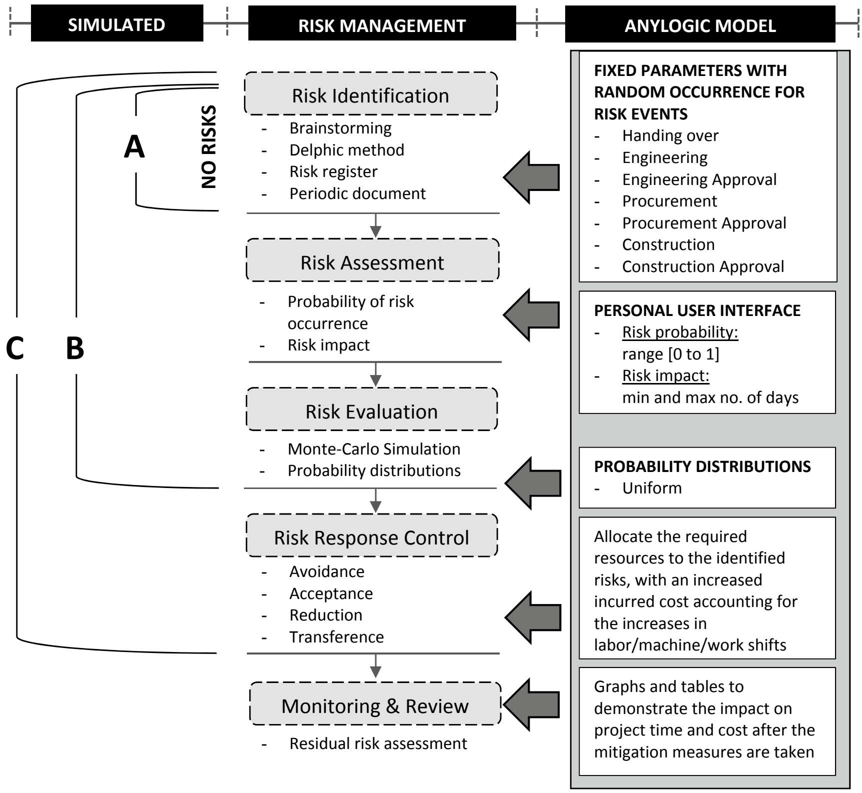


Fig. 1 Proposed methodology

the authors indicate four main phases in the construction process, along with their approval stages which are commonly subjected to delays in the completion of the required activities. Table 1 identifies possible causes of delay for each of the four phases.

2.2 *Monte Carlo Simulation*

The Monte Carlo simulation-based approach is a sampling-based method commonly used in the evaluation of construction project risks [34]. During a Monte Carlo simulation, random values are generated from a variety of specific probability distributions [15, 27], as such a behavior is allocated to the specific range of random values with an inherent uncertainty [16]. The model is then iterated thousands of times, each time using different random values based on each input values specific probability distribution, producing distributions of all possible outcome values [21].

Table 1 Possible delay causes in the construction industry

Delay cause	References
1. Handover	
Project variation	[25]
Inability of client to pay the contractor	[25]
Inaccurate site investigation	[7]
Unsuitable subsurface site conditions (soil, high water table, etc.)	[23]
New government policies	[25]
2. Engineering	
Incomplete design scope	[17]
Design errors	[17]
Inadequate specifications	[17]
Design changes by client	[7]
Inadequate details in design drawings	[7]
3. Procurement	
Delay in manufacturing materials	[7]
Late delivery of materials	[7]
Shortage of construction materials	[7]
Poor procurement of construction materials	[7]
Unreliable suppliers	[7]
4. Construction	
Insolvency during the construction process from the contractor and/or client	[22]
Adverse weather conditions	[22]
Untrained construction staff	[22]
Unsustainable timeframe	[22]
Unavailability of utilities in site	[22]
Equipment failure	[17]

The AnyLogic software incorporates approximately 25 distributions. In the literature, there are several different probability distributions used in the applications of the Monte Carlo simulation in project risk management. Agarwal and Mahajan [3] proposed the use of three probability distribution functions, PERT distribution, normal distribution, and triangular distribution to assess the risks associated with delays in construction activities which affect the overall construction project schedule. Similarly, AbouRizk and Halpin conducted a study for seventy-one samples of construction activity duration patterns and determined that the beta distribution is the most appropriate function for the representation of construction activity durations [2].

2.3 Agent-Based Modeling Simulation in the Construction Industry

Agent-based modeling (ABMS) is based on three principal aspects: the combination of agents; agent relationships; and the agent environment, to generate the required outputs. Agents are active decision-making entities, executing various behaviors varying from simple to complex, depending on the represented situation and system [10, 32]. The identification of agents is the initial step in the in the ABMS, in which each agent has a distinct attribute, responsible for its behavior in the system. Agent relationships signify both the interactions between all agents in a system and between the agents and their surrounding environment, which represent the agent's environment [32].

3 Methodology

In this section, the proposed process for developing a simulation-based risk management model is presented, as identified in Fig. 1. The model has been developed for repetitive projects for constructing medium-sized buildings. For simplicity, the project activities are grouped to have the following sequence.

- Stage 1—Site handing over: Client to hand over the site to the contractor as such, the commencement for the project would be considered.
- Stage 2—Engineering: Developing the engineering deliverables by the contractor.
- Stage 3—Engineering approval: Engineer to approve the engineering deliverables.
- Stage 4—Procurement: Contractor to perform the procurement activities for the materials that would be use during the construction.
- Stage 5—Procurement approval: Engineer to approve the procured material deliverables.
- Stage 6—Construction: Contractor to perform construction activities.
- Stage 7—Construction approval: Engineer to approve the constructed works.
- Stage 8—Project finish: Contractor to hand over the project to the client.

3.1 Model Objectives

The objectives of developed model are to:

1. Establish a tool to estimate the total duration and the needed relative resources during the bidding phase.
2. Provide stakeholders with a flexible user interface based on their expert judgment to define the risk probability and impacts.
3. Provide a visual representation of outputs.
4. Allow project stakeholders to forecast the cost for all simulated project scenarios.

5. Provide the flexible adjustment of the risk management techniques based on the constraints of time and cost.

3.2 Scenario Description

The developed model considers three scenarios:

1. The first scenario has no risks at all.
2. The second scenario has the risks occurred.
3. The third scenario has the risks occurred, and the mitigation actions have been taken.

The risks are presented via random event. Once the event happens, a consequential delay and costs shall be added for each stage. This consequential delay shall follow a uniformly distributed delay time with a minimum and a maximum duration inserted by the model's user for each stage. The mitigation control is introduced, through a decision by the model user, as a percentage which 100% means fully mitigated, and in this case, the duration would be close to the first scenario. While 0% means no mitigation at all, as such, the duration would be like the second scenario.

The cost for each stage is concluded by the following formula:

$$\text{The cost per stage} = \text{the total cost per day inserted by the user} * \text{the stage duration.}$$

The total cost per day could be assumed to be equal to the total contracted value divided by the total planned duration. The cost for the mitigation is assumed to be uplifted over the regular cost per day with the same mitigation percentage introduced by the user.

3.3 Simulation Model Formulation

The three developed models for the three different scenarios indicated above are shown in Fig. 2.

3.4 Simulation Libraries and Parameters

The risk event is developed based on several variables as illustrated in Fig. 3. The ONOFF variable is a randomly generated number between 0 and 1 and is generated for every simulation case. If this variable is greater than the risk probability provided by the user, another variable is introduced, identified in in the second column of variables ex. HO_P_E, which is equivalent to a uniform value between the minimum

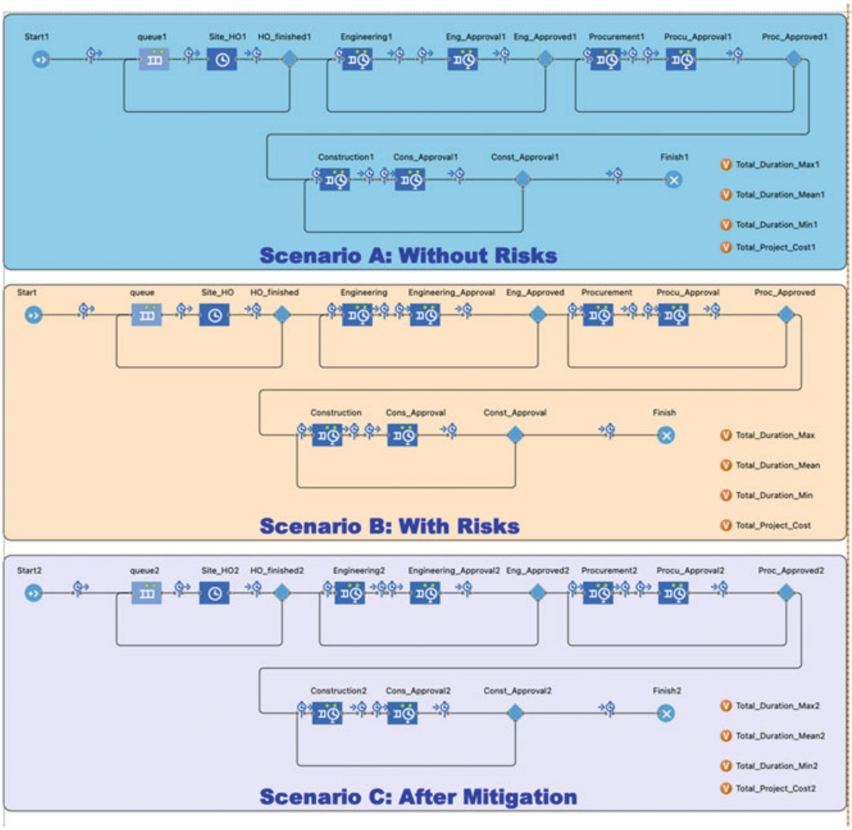


Fig. 2 Scenarios in the developed simulation model

and maximum risk impact, which is also introduced by the user. Otherwise, if the ONOFF variable is less than the risk probability provided by the user, the associated risk impact shall equal zero, and no risk occurs.

Fig. 3 Risk event modeling criteria

As indicated in Table 2, each stage is assumed to use the following duration distribution:

It is assumed that 70% of the handing over, engineering, procurement, and construction activities would grant the engineering approval. In case the engineering has rejected the activity, it should be subject to a rework until it receives approval.

The simulation steps and input values for each of the three scenarios are illustrated in Tables 3, 4, and 5.

Table 2 Duration distributions

Stage	Duration distribution in days
Stage 1—Site handing over	Uniform(0, 7)
Stage 2—Engineering	Triangular(5, 30, 60)
Stage 3—Engineering approval	Uniform(1, 7)
Stage 4—Procurement	Uniform(2, 90)
Stage 5—Procurement approval	Uniform(1, 7)
Stage 6—Construction	Pert(7, 360, 90)
Stage 7—Construction approval	Uniform(1, 7)
Stage 8—Project finish	1

Table 3 Simulation steps and input values (Scenario A)

Simulation components	Identification	Input values
Source	Start1	Calls of inject () function *After finishing each simulation case*
Delay	Site_HO1	Uniform(0, 7)
Output	HO_Finished1	0.7
Service	Engineering1	Triangular(5, 30, 60)
Service	Engineering_Approval1	Uniform(1, 7)
Output	Engineering_Approved1	0.7
Service	Procurement1	Uniform(2, 90)
Service	Procu_Approval1	Uniform(1, 7)
Output	Procu_Approved1	0.8
Service	Construction1	Pert(7, 360, 90)
Service	Const_Approval1	Uniform(1, 7)
Output	Const_Approved1	0.8
Sink	Finish1	None

Table 4 Simulation steps and input values (Scenario B)

Simulation components	Identification	Input values
Source	Start	Calls of inject () function *After finishing each simulation case*
Delay	Site_HO	Uniform(0, 7) + HO_P_E
Output	HO_Finished	0.7
Service	Engineering	Triangular(5, 30, 60) + Eng_P_E
Service	Engineering_Approval	Uniform(1, 7) + Eng_Appr_P_E
Output	Engineering_Approved	0.7
Service	Procurement	Uniform(2, 90) + Proc_P_E
Service	Procu_Approval	Uniform(1, 7) + Proc_App_P_E
Output	Procu_Approved	0.8
Service	Construction	Pert(7, 360, 90) + Const_P_E
Service	Const_Approval	Uniform(1, 7) + Const_App_P_E
Output	Const_Approved	0.8
Sink	Finish	None

Table 5 Simulation steps and input values (Scenario C)

Simulation components	Identification	Input values
Source	Start2	Calls of inject () function *After finishing each simulation case*
Delay	Site_HO2	Uniform(0, 7) + HO_P_E − (HO_P_E * Mitigation)
Output	HO_Finished2	0.7
Service	Engineering2	(Triangular(5, 30, 60) + Eng_P_E) − (Eng_P_E * Mitigation)
Service	Engineering_Approval2	(Uniform(1, 7) + Eng_Appr_P_E) − (Eng_Appr_P_E * Mitigation)
Output	Engineering_Approved2	0.7
Service	Procurement2	(Uniform(2, 90) + Proc_P_E) − (Proc_P_E * Mitigation)
Service	Procu_Approval2	(Uniform(1, 7) + Proc_App_P_E) − (Proc_App_P_E * Mitigation)
Output	Procu_Approved2	0.8
Service	Construction2	(Pert(7, 360, 90) + Const_P_E) − (Const_P_E * Mitigation)
Service	Const_Approval2	(Uniform(1, 7) + Const_App_P_E) − (Const_App_P_E * Mitigation)
Output	Const_Approved2	0.8
Sink	Finish2	None

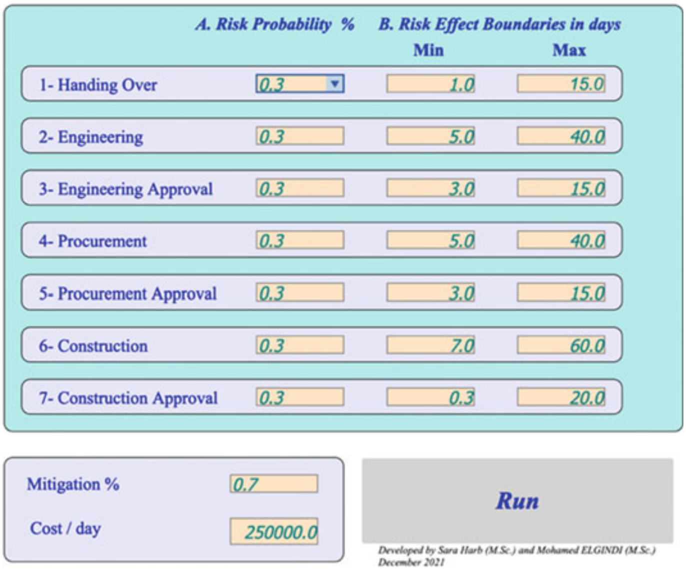


Fig. 4 User interface in simulated model

3.5 Running the AnyLogic Model

As shown in Fig. 4, the user interface allows the user to enter the following values:

1. Risk probability percentage within the range of 0–1, with 0.1 intervals
2. Risk effect minimum and maximum values, in days
3. Initial targeted mitigation percentage
4. Cost per day.

The model runs 10,000 simulation case, where each represents the duration of one project.

3.6 Model Verification and Validation

The model has been run based on a 70% mitigation value. As shown in Fig. 5, the results indicate rational values. Since the duration for the risks for the 'with risk' scenario is the highest time, followed by the 'after-mitigation' scenario, the lowest time is recorded for the 'without risks'. Similarly, the highest cost is recorded for the 'after-mitigation' scenario, followed by the 'with risks', ending with the 'without risks' scenario.

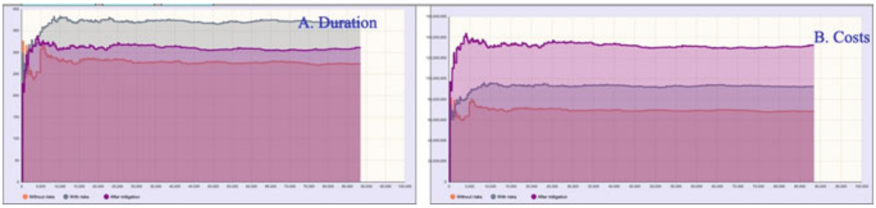


Fig. 5 Duration and costs at 70% mitigation value

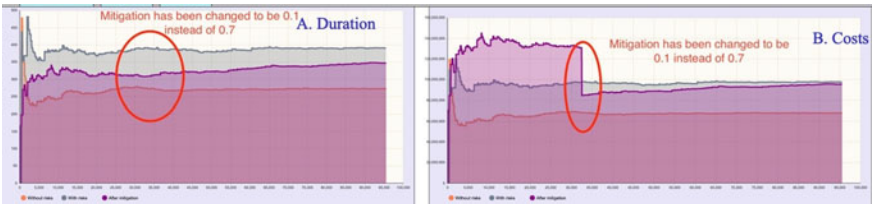


Fig. 6 Duration and costs at 10% mitigation value

Another validation tool is represented in Fig. 6, as it signifies the effectiveness of the mitigation decision on the recorded results. This is demonstrated by the sudden drop as the mitigation value has been decreased based on the user's input.

4 Results

Once the model is run, a dashboard of graphs appears to the user, with three tabs at the top. One shows the processing logic, one for the graphs, and the third tab for some tables.

The mean durations for each of the four activities and their associated approvals are illustrated in Figs. 7, 8, 9, 10 and 11. Figure 12 presents the duration project distribution function (PDF) and cumulative distribution function for the three scenarios. The total duration is illustrated in Fig. 13, while the total costs are presented in Fig. 14. A slider presents the mitigation percentage and is introduced to the model as shown in Fig. 15. At any given point, the user can adjust the percentage, which updates the results instantly. Worth noting that this slider is used to validate the model's credibility. The tables tab introduces another presentation for the model results as shown in Fig. 16. It gives an idea about the duration and the associated costs for each group of activities in the three scenarios and the overall cost figures as well. It also has a slider for mitigation, as described before.

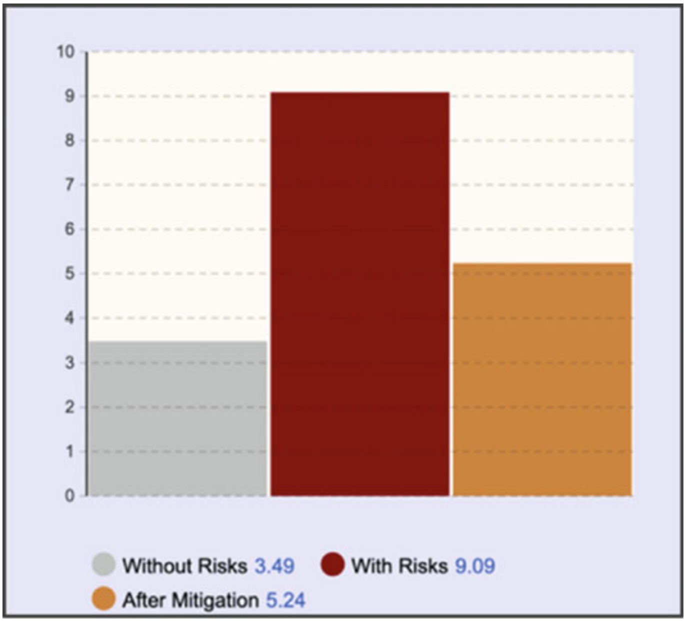


Fig. 7 Handing over activity mean durations/days

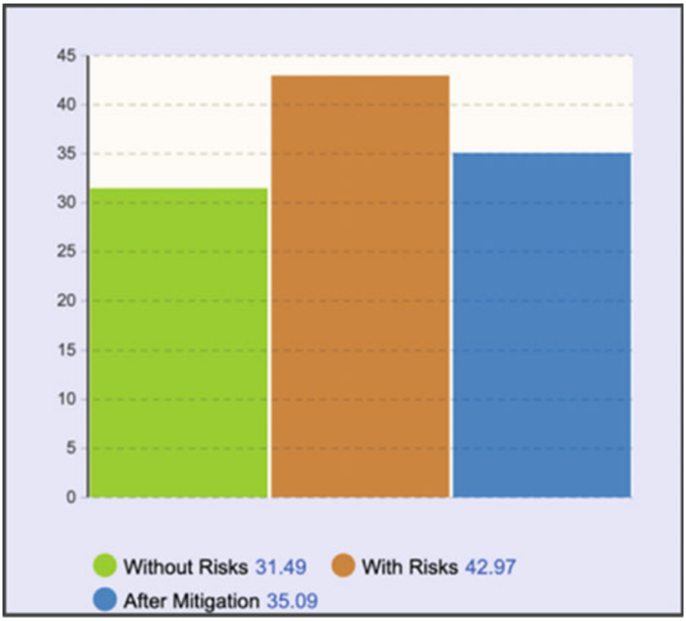


Fig. 8 Engineering activity mean durations/days

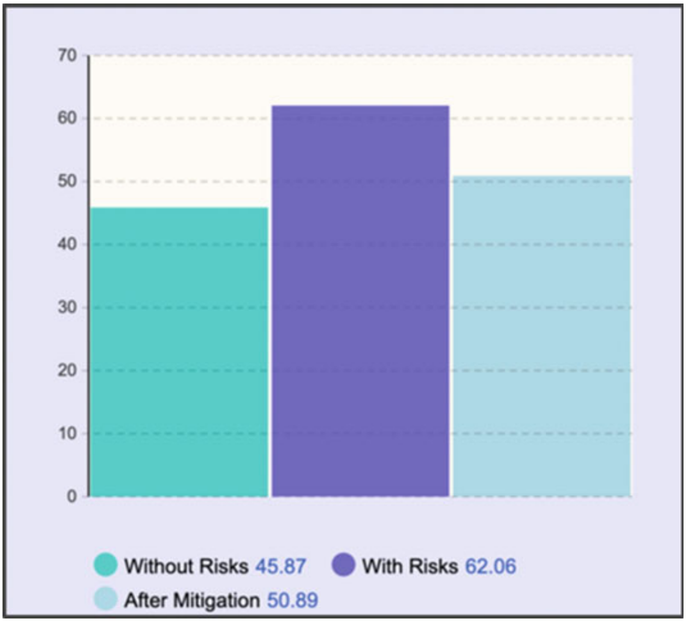


Fig. 9 Procurement activity mean durations/days

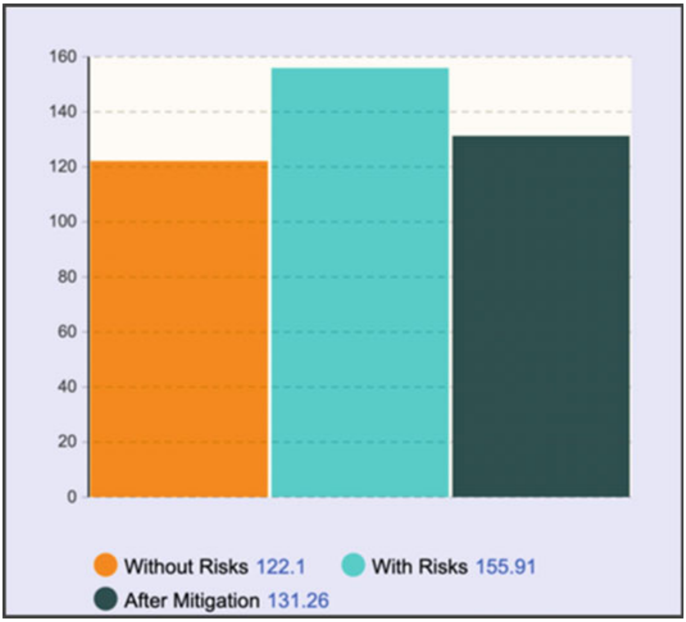


Fig. 10 Construction activity mean durations/days

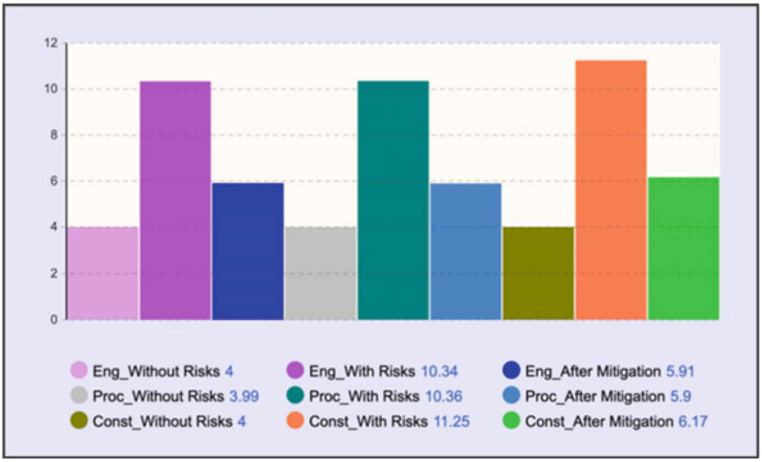


Fig. 11 Approval durations for engineering, procurement, and construction activities/days

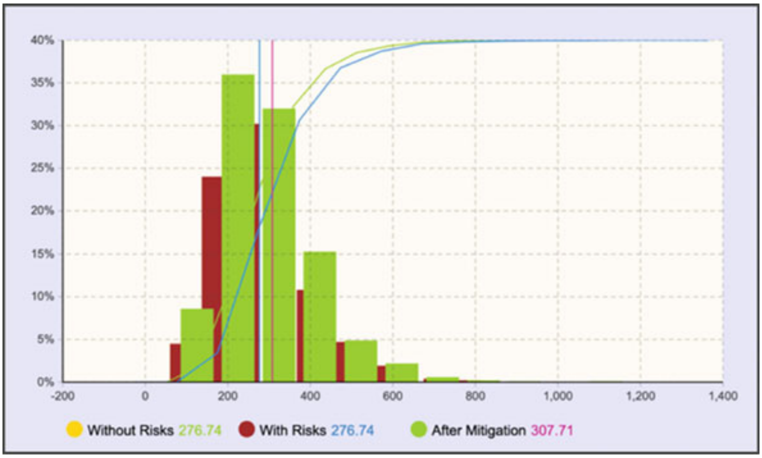


Fig. 12 Total project duration distribution for the three scenarios/days

5 Conclusions

In construction industry, projects are usually vulnerable for prolongation risks more than the planned duration. The prediction of the risks before it occurs is a proactive technique that would assist the project managers to control the impacts resulting from thereof. The authors introduce an agent-based simulation model using AnyLogic software for the risk analysis of the project schedule.

The developed model provides reliable and comprehensive results that give the user a chance to decide the proper control over the occurred risks. The model through

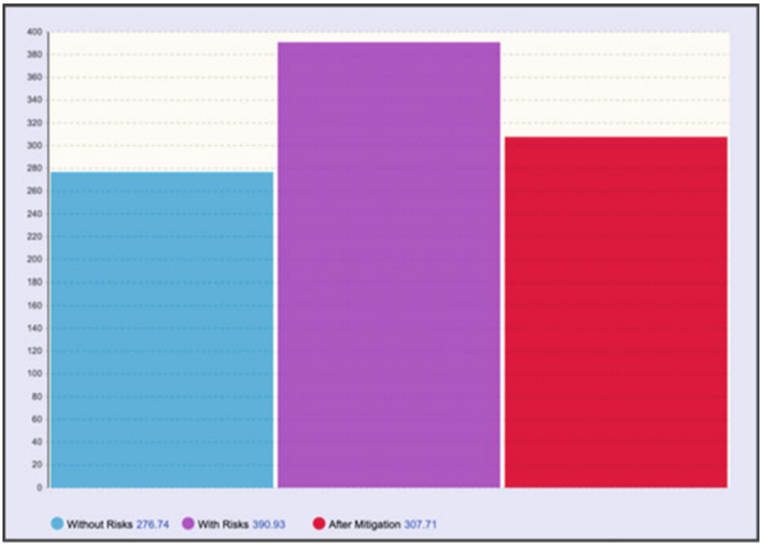


Fig. 13 Total duration for the three scenarios/days

Fig. 14 Total cost for the three scenarios/days

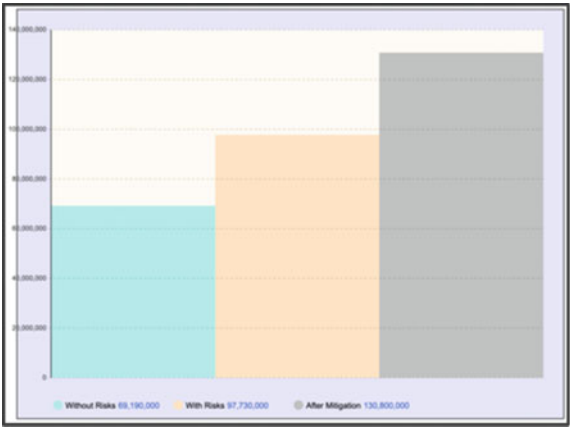
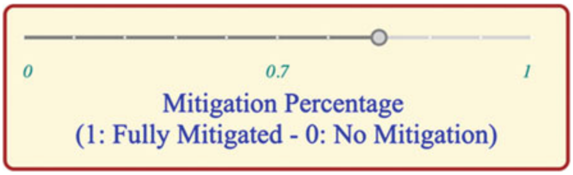


Fig. 15 Slider tool to adjust the risk mitigation percentage



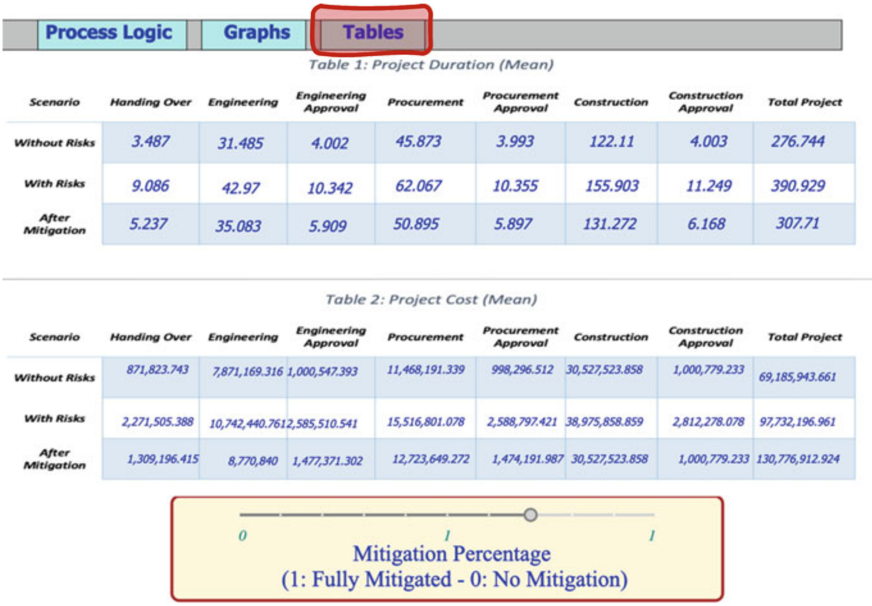


Table 1: Project Duration (Mean)

Scenario	Handing Over	Engineering	Engineering Approval	Procurement	Procurement Approval	Construction	Construction Approval	Total Project
Without Risks	3.487	31.485	4.002	45.873	3.993	122.11	4.003	276.744
With Risks	9.086	42.97	10.342	62.067	10.355	155.903	11.249	390.929
After Mitigation	5.237	35.083	5.909	50.895	5.897	131.272	6.168	307.71

Table 2: Project Cost (Mean)

Scenario	Handing Over	Engineering	Engineering Approval	Procurement	Procurement Approval	Construction	Construction Approval	Total Project
Without Risks	871,823.743	7,871,169.316	1,000,547.393	11,468,191.339	998,296.512	30,527,523.858	1,000,779.233	69,185,943.661
With Risks	2,271,505.388	10,742,440.761	2,585,510.541	15,516,801.078	2,588,797.421	38,975,858.859	2,812,278.078	97,732,196.961
After Mitigation	1,309,196.415	8,770,840	1,477,371.302	12,723,649.272	1,474,191.987	30,527,523.858	1,000,779.233	130,776,912.924

Fig. 16 Snapshot from the tables tab in the model simulation

10,000 runs shall simulate the project duration with the predictable risks. The user shall decide the mitigation protocol he would use according to his priority to overcome the occurred risk impacts; duration over costs, costs over the duration, or a balance between both.

The model has proven to have the following benefits:

- It can be used in the bidding phase to estimate the total duration and the needed relative resources.
- Forecasting the costs for all three scenarios.
- Flexible adjustment of the mitigation techniques. Time versus cost.
- Provide user with a flexible user interface based on their expert judgment to define the risk probability and impacts.
- Visual representation of outputs which is beneficial to project stakeholders.
- Allow decision-makers to explore the impact of risks on the project schedule and cost.

5.1 Suggestions for Further Research

For extending the given work and increasing the applicability of its framework, it would be possible to further break down the construction activities and introduce other risks in the risk management process, rather than just the schedule-related ones. Linking the model to planning softwares, as such Primavera, or Microsoft Projects could transfer the input into the AnyLogic visa JavaScript. This model used a uniform distribution for risk impacts to simplify the developed model, whereas the activities delays have been considered for the use of different distributions, such as uniform, PERT, and triangular as indicated in Tables 3, 4 and 5. Further research could include additional probability distributions for both risks and activities delays. The introduction of resource pools and its associated costs per each resource type would provide more accurate cost calculations.

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