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Research Article

Overall Cost Overrun Estimate in Residential Projects: A Hybrid Dynamics Approach

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Residential projects are described as complex, dynamic systems that are subject to uncertainty. Cost performance is a fundamental challenge. As a result, project managers must adequately identify risks that might lead to cost overruns in residential construction projects. Simulation is noticed to be a useful technique for dealing with these complications. Therefore, this study developed a hybrid dynamic approach to study the effect of different risks on the cost performance of construction projects. The proposed approach combines system dynamics (SD) and discrete event simulation (DES), which can take into consideration the dynamics of the project environment, which contains various continuous influencing factors as well as the construction operations. The developed hybrid model is validated through serial model structure tests and model behavior tests, with the aid of data collected from a real construction project used in the simulation process. Based on the simulation results, it is concluded that the proposed hybrid dynamic approach is helpful to enhance the process performance by permitting construction managers to identify possible process improvement areas that traditional methods may miss.

1. Introduction

Engineers, surveyors, laborers, accountants, marketers, and attorneys all play important roles in the construction industry, which contributes significantly to GDP, investment, and job prospects in both developed and developing nations [1]. Various risks, however, have an impact on cost performance, generating cost overruns that employers might result in delays, stakeholder conflicts, and a decrease in owner return on investment.

Since the turn of the century, several traditional approaches for analyzing cost overrun risks have been presented, including the critical path method (CPM), the last evolution of the precedence diagramming method (PDM), and the program evaluation and review technique (PERT) [2]. Traditional approaches break the entire job into smaller sections called activities, which may then be processed and modeled; however, traditional methods neglect the dynamics and interdependencies among these activities [3]. Traditional approaches presume that construction projects are simple and static, but in reality, they are more complicated and dynamic. At the strategic and operational levels, simulation-based models are being investigated. Strategic project management aims to make judgments during the design phase that will drive later operational decisions, ensuring that these operational decisions are compatible with project performance over the long term [4].

The system dynamics models simulate dynamic systems in the real world, giving the ability to simulate what could happen in the future and understand the impact on multiple key metrics [5]. Meanwhile, DES assists administrators in making informed facility design decisions prior to making actual investments in renovations and new projects [6].

This study is primarily concerned with construction project control methods (particularly residential projects) that may result in cost overruns. Several researches have been carried out to estimate the cost of the residential projects as well as investigate the cost overrun, but few efforts have considered the dynamic changes throughout the construction period. Moreover, most of the previous studies were conducted only from the macro or micro level rather than both levels and did not clearly integrate the unexpected events. Thus, this research proposed a hybrid SD-DES model by first identifying the influencing cost risks in the literature, followed by a questionnaire survey and data analysis, using the importance index method. Then, the developed model will be bounded, and causal relationships will be formed in a causal loop diagram, which will be followed by developing mathematical equations using the stock-flow diagram. To allow a better understanding of cost performance from a strategic level, as a consequence, the SD model will be encapsulated into an event in DES, which resulted in two modules: task and continuity, which is being tested using the Al Alamein Residence building in Egypt, and then a simulation study is carried out to describe the dynamics of the rework cycle and its influence on time and cost, the material management cycle, the workforce management cycle, and the influence of the unexpected events on the project, which decision-makers may overlook using traditional approaches.

The objectives of this research are as follows: (1) to develop a hybrid dynamic model for simulating possible impacts of major risks on the planned budget of construction projects, (2) to validate the developed model for building up confidence before simulation analysis, and (3) to conduct simulation analysis to investigate the possible impact of various risks on the total cost of the construction project. The hybrid dynamic model developed in this research forms an innovative tool for helping construction managers identify possible process improvement areas that traditional methods may miss. The proposed hybrid model in this paper can be used to discover the causes for the cost overrun and analyze its impacts on construction projects that finally aim at reaching a fair balancing of cost, time, and quality.

2. Literature Review

System dynamics modeling, as a part of the learning process, is a continuous process in which hypotheses are formulated, tested, and revised for both formal and mental models [7], while discrete event simulation (DES) assumes that the system state is changed according to the set of activities happening in the time slice, as DES analyzes the construction process with an event-oriented view [8]. Numerous researchers used the system dynamics model, and others used discrete event simulation in construction project management to find a way to overcome several dynamic issues that come up in complex construction projects. For a clear visualization, a summary of previous studies' outcomes is tabulated to justify the current study's contribution (Table 1).

Although SD modeling is capable of effectively considering feedback processes [3], it cannot reflect operational level risks as it cannot deal with subdivided consecutive activities [20]. Eventually, to compensate for these shortcomings and gain the benefits of SD modeling, the combination with an operational technique such as DES is preferable to provide more accurate representations of reality.

On the other hand, discrete event simulation is considered an effective tool in the quantitative analysis of the events in the entire construction life cycle; however, it cannot reflect the feedback in the construction process [21].

It would therefore be preferable to use an SD model for strategic project management and a DES model for operational project management. Both SD and DES can be considered complementary to one another, and the limitations related to each can be overcome when both methods are integrated, so researchers began to experiment with combining SD and DES resulting in hybrid SD-DES models as illustrated in Table 1. Although the previous SD-DES models considered strategic as well as operational issues, it still shows some limitations, as most of the preceding SD-DES models can only be developed for a certain project; once the activity on the project node network changes, the original model will be no longer applicable. Moreover, most previous studies have focused on one of the events affecting project performance neither examining risks scaled to the whole project.

In fact, the system dynamics modeling in addition to discrete event simulation had several applications in project management; however, there are many dynamic features of large construction projects; especially residential projects still need to be further investigated. For example, the cycle of inspecting the completed works from the contractor's and the consultant's point of view, the probability of scope change and its effect on the project time and cost, the material resources management process, the workforce hire-quit cycle, and the rework and their effects on project performance.

The literature review shows that there is a research gap in the previous models. Most previous studies have focused on one of the events affecting project performance; however, construction projects, according to Sterman [7], frequently appear to be going smoothly until a chain of events occurs resulting in overruns and delays. The simultaneous impacts of several factors influencing performance have not yet been investigated. Moreover, the preceding SD-DES models can only be developed for a certain project; once the activity on the node network of the project changes the original model will be no longer applicable.

The main contributions of this paper that fulfill the previous research gap are as follows: this study proposes a hybrid dynamics model for a better cost estimate that considers the complex, interrelated structure of various influencing factors. Moreover, the presented model provides different scenarios that allow managers to understand the cost performance and select the proper policy to avoid or eliminate the cost overrun. The proposed hybrid SD-DES encapsulates the SD model into each event in the DES model. The SD model is used for macroanalysis to investigate the strategic issues; meanwhile, DES is used for microanalysis to investigate the operational issues.

3. Research Methodology

The proposed model in this research consists of two simulation-based tools, namely system dynamics (SD) and discrete event simulation. Based on Sterman's [7] modeling, the system dynamics formulation in this research goes

Table 1: Classified scheme of the existing literature on project management.

References	Contribution of research	Simulation technique
Alvanchi et al. [9]	Proposed a hybrid SD and DES simulation approach as a comprehensive simulation framework for construction management from construction operation and construction context	Hybrid SD-DES
González and Echaveguren [10]	Integrated environmental and traffic models to incorporate environmental goals in the design of road construction operations, in terms of fugitive and exhaust emissions produced by the production and traffic conditions	DES
Han et al. [11]	Examined the dynamics of design defects and their impact on project performance	SD
Alzraiee [12]	Suggested a new method that integrates DES and SD models to address the operational and soft/strategic variables on a single computation platform, which results in realistic project schedule networks, and that allows understanding of the interactions of the project's parameters	Hybrid SD-DES
Jiang et al. [13]	Analyzed the safety performance under various causes using different site scenarios	SD
Moradi et al. [14]	Proposed a theoretical framework for a hybrid continuous-discrete simulation approach that can take into account the dynamics of the project environment arising from the complex interrelated structure of different continuous influencing factors likewise the construction operations	Hybrid SD-DES
Wang and Yuan [15]	Investigated the risk effects on schedule delay in infrastructure projects concerning simulation-based scheduling	SD
Osman et al. [16]	Organized the repair process of water pipes crews across water network break sites in an urban setting	DES
Forcael et al. [8]	Developed simplified scheduling of a building construction process	DES
Oleghe and Salonitis [17]	Developed a framework for analyzing problems associated with multifaceted elements, which interact and evolve over time	Hybrid SD-DES
Kim et al. [18]	Constructed an integrated system dynamics model to describe the dynamic interdependence of the causes and impacts of skilled labor shortages in construction projects	SD
Li et al. [19]	Explore how multilevel motivations interact with designers' sustainable buildings	SD
Current study	Propose hybrid SD-DES that encapsulates the SD model into each event in the DES model in addition to presenting different scenarios, which allow managers to understand the cost performance and select the proper policy to avoid or eliminate the cost overrun	Hybrid SD-DES

through four stages: conceptualization, formulation, testing, and simulation. Then, the SD model was encapsulated into each event in the DES model to form the hybrid SD-DES approach. To facilitate the conceptual design phase of the hybrid model development an illustrative framework is proposed. This framework is summarized in Figure 1 as follows: (1) identify critical risks that impact cost performance on construction projects in consideration of relevant stakeholders, (2) perform qualitative and quantitative analyses based on systems thinking, (3) validate system parameters and interactions with the aid of Anylogic® software package, (4) develop a hybrid dynamic model for evaluating and simulating the probable impact of the identified critical risks on cost performance in the construction projects, and (5) conduct a scenario analysis to assess the impact of the cost risk scenarios that have been developed.

4. Cost Risks Identification

Badawy et al. described the project risk factor as an event that may take place causing a positive or negative influence on one or more project objectives such as time, cost, and quality [22]. To identify critical risks that impact the cost performance of residential projects, three steps are carried out. First, a review of existing literature on project risks was performed resulting in formulating a list of 32 cost risks related to different stakeholders that have a direct influence on the cost of the construction projects as illustrated in Table 2.

Second, a questionnaire survey was conducted; the questionnaire was divided into two sections. The first section aimed to collect respondents' background information; therefore, the questionnaire was distributed among major stakeholders in construction projects, including project owners, consultants, and contractors. All respondents had a good understanding of project risk management. A total of 200 questionnaires were sent out, and eventually 165 valid responses were received, reaching a valid responding rate of 82%. The respondents could be classified as 148 male and 17 female—38 owners, 56 consultants, and 71 contractors—15 with less than 2 years of work experience, 29 with 2–5 years of work experience, 68 with 6–10 years of work experience, and 53 with more than 10 years of work experience. The second section contained the 32 risks to be evaluated. The respondents evaluated the probability of the risk occurrence and the degree of severity for each risk based on their experience according to a six-point scale as follows: (0: not going to happen/no effect, 1: very low, 2: low, 3: medium, 4: high, and 5: very high). Third, the data were analyzed by determining the Probability Index (P.I.), the Severity Index (S.I.), the Importance Index (IMP.I.), and the Spearman rank correlation (r_s) using the following equations:

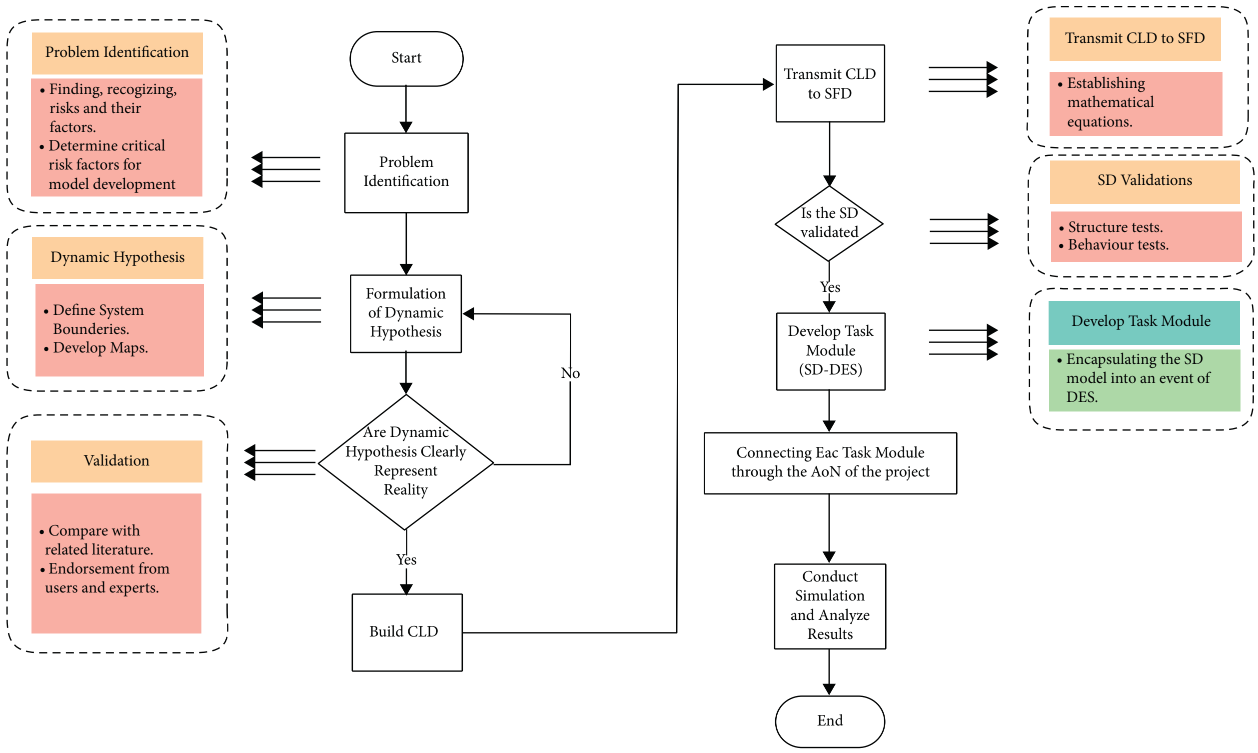

Figure 1: Modeling process methodology.

$$\begin{aligned} \text{P.I.}\,(\%) &= \sum \frac{a \cdot n}{6 \cdot N} \times 100, \\ \text{S.I.}\,(\%) &= \sum \frac{a \cdot n}{6 \cdot N} \times 100, \\ \text{IMP.I.}\,(\%) &= \frac{[\text{P.I.}\,(\%) * \text{S.I.}\,(\%)]}{100}, \\ r_s &= 1 - \left[\frac{6 \sum d^2}{\left(n^3 - n\right)}\right], \end{aligned} \tag{1}$$

where a is the value representing weighting given by each response, n is the number of responses choosing a value, N: is the total number of responses, r_s is the Spearman rank correlation coefficient between two parties, d is the difference between ranks assigned to variables for each risk, and n is the number of pairs of rank. The correlation coefficient fluctuates between +1 that indicates a perfect positive relationship (agreement) and −1 that indicates a perfect negative relationship (disagreement).

The analysis results on the most critical risks influencing the cost of the construction projects according to their important index (IM.I.), which are illustrated in Table 3. These risks are used for further simulation analysis by the hybrid dynamic model.

5. System Dynamics Model Development

System dynamics includes several techniques for dealing with feedforward connections while considering both the hard and soft characteristics of a system. The system dynamics framework in this study includes the following tools, according to Sterman's [7] model, boundary diagrams, causal loop diagrams, and stock-flow diagrams.

5.1. Model Boundary. A system is a collection of elements that work together to accomplish a defined purpose. Changes in the system caused by endogenous factors have an impact on it. Meanwhile, changes in the system environment caused by external factors have an impact on the system. The boundaries between the system and its surroundings are established under the study's objectives [31]. Excluded variables are variables that are carefully left out of the causal-effect feedback mechanism. The model was bounded as indicated in Figure 2 based on the risk identification described in the prior section.

5.2. Causal-Loop Diagram. A causal-loop diagram (CLD) is created once the model boundaries are defined to highlight causal links among the main variables in the construction management system. The causal-loop diagram (CLD) is a diagram that helps in comprehending the feedback system (interactions between the system's components) in complicated connections. It is made up of variables that are connected by arrows that represent causal linkages. The primary loops are identified by a loop identifier, which indicates whether the loop is reinforcing or balancing [7].

According to Figure 3, a rise in "Total Work Quantity" leads to an increase in "Remaining Works," which is followed by an increase in "Completed Works," which indicates that the job is finished but not yet inspected. As the number of finished works rises, so do the number of faults in the job, increasing

Table 2: Cost risks in construction projects.

Stakeholder	Cause of cost overrun	References
Owner	Delay in progress payments by the owner Lack of detail and definition, incomplete, or incorrect design brief Change in orders by the client Change in the scope of the project Long period between design and time of tendering.	[23–25]
Consultant	Project design complexity Inadequate planning and scheduling Mistakes and discrepancies in design documents Unclear and inadequate details in drawings Delays in producing design documents Delays due to approval procedures	[26, 27]
Contractor	Increase in manpower cost due to environmental restrictions, insurance premiums, and other social expenses of the workforce Low labor performance Waste rate of materials Delay in material delivery Shortage of equipment Equipment breakdowns Low level of equipment operator's skill Increment of equipment's/equipment's maintenance prices	[24, 28, 29]
Subcontractor	Mistakes during construction Lack of subcontractor skills Improper construction method by subcontractor	[27]
External factors	Political situation Social and cultural impacts Effect of weather conditions Fluctuation in prices of raw materials government regulation and control level Unforeseen ground conditions Accident during construction Fuel shortages Natural disasters Strikes and demonstrations	[24, 29, 30]

Table 3: Critical risks influencing cost performance.

Critical risk	Risk description	IM.I.	Dimensions
CRDC	Change requests during construction	28.13	Owners-related
URIMP	Unexpected rise in material prices	27.34	External-related
SOE	Shortage of equipment	25.78	Contractors-related
RDTM	Rework due to mistakes	24.22	Contractors-related
CIPD	Change in project duration	23.87	Owners-related

"Undetected Rework," the quantity of "Known Rework" rises when faults are discovered, which causes "Remaining Works" to be escalated again in the reinforcing loop (*R*1). When "Total Work Quantity," which is influenced by "Initial Work Quantity" and "Scope Changes Work Quantity," rises in the balancing loop (*B*1), "Remaining Works" rises as well. As a result, the number of "Completed Works" rises. As a result, "Verified Works" increases, "Completion Percentage" increases, and "Total Work Quantity" decreases. When the "Remaining Time for Completion," which is directly influenced by "Remaining Works," grows in the balancing loop (*B*2), the "Duration" increases as well, and the "Schedule Pressure" arises as a result. To counteract the negative effects of "Schedule Pressure" on job quality, "Amount of Overtime" should be increased. "Remaining Time for Completion" diminishes over time when work hours are increased within the maximum permissible work hours.

5.3. Model Stock-Flow Diagram. The proposed preliminary SD model was derived from the model given by [11, 15, 19, 32–34]. Following that, their initial model was improved to replicate cost performance in residential constructions. Seven functional subsystems (as shown in Figure 4) underpin the logic of the SD model, including:

(1) Project scope subsystem: changes in the owner's requests, design drawings, unique construction circumstances, and other change orders might cause changes in the project scope, causing schedule delays and cost overruns [22]. In the early phases of the project, the boundaries and constraints are evident, but as the construction develops, scope changes arise, thus the percentage of scope change and the time required to demand scope changes are established in the model from the beginning. As a result, this subsystem reflects the initially planned work as

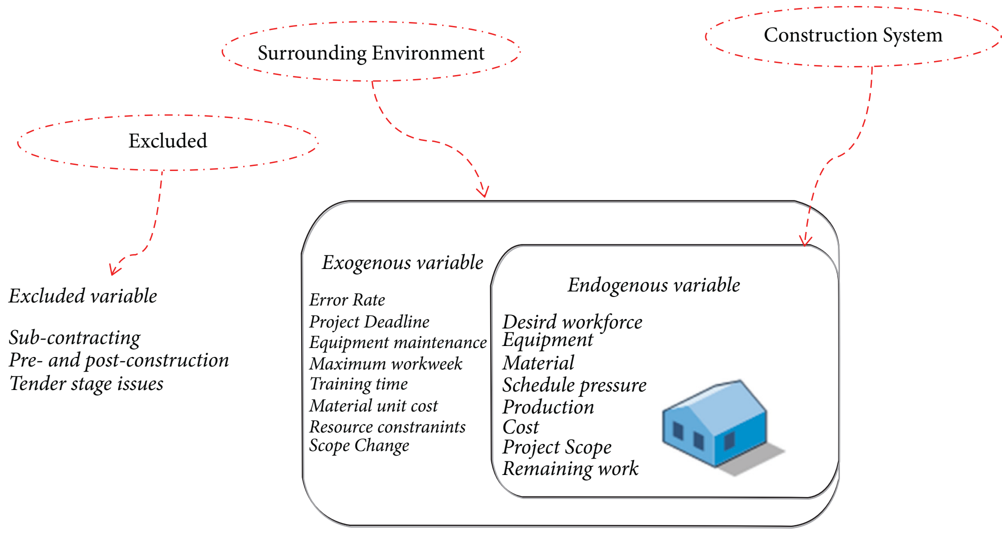

Figure 2: Model boundary variables.

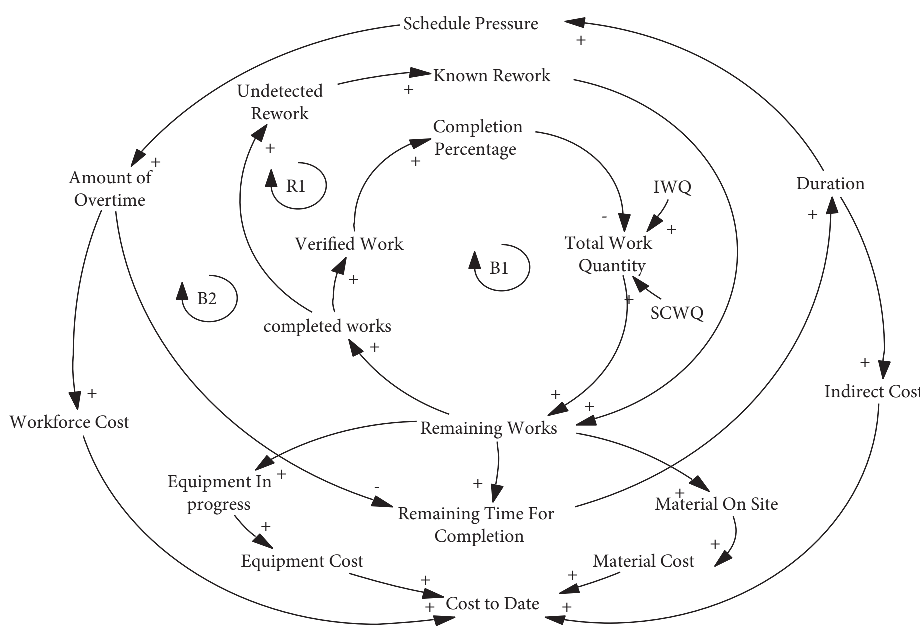

Figure 3: Feedback structure for residential projects.

well as the desired additional work, specifying the amount of scale change work that will be injected into the work-rework process cycle.

(2) Work and rework subsystem: this subsystem represents the entire work to be performed in a specific quality until it is completed, including the contractor's quality control team detecting the work quality, followed by the consultant team inspecting the work and identifying the defective work, which is returned to the workers for improvement or rework until the quality requirements are met and the completion rate reaches 100%.

(3) Material management subsystem: this subsystem is intended to reflect the material management cycle, which begins with the ordering of planned anticipated material and continues through material inspection and use in production until the raw material is transformed into productive or waste material. The garbage is separated into waste that may be reused and waste that must be disposed of.

(4) Workforce management subsystem: this subsystem is concerned with the manpower required to complete a job with a specified level of quality. To satisfy the project's needs, labor production must be at a reasonable pace; if this rate cannot be met, the management must either raise the necessary workforce or work overtime. To become a skilled workforce, the newly hired labor requires time to be taught.

(5) Equipment management subsystem: the equipment employed in the building process is expected to function at a fixed theoretical rate, but in fact, this rate is modified by equipment lifetime, weather

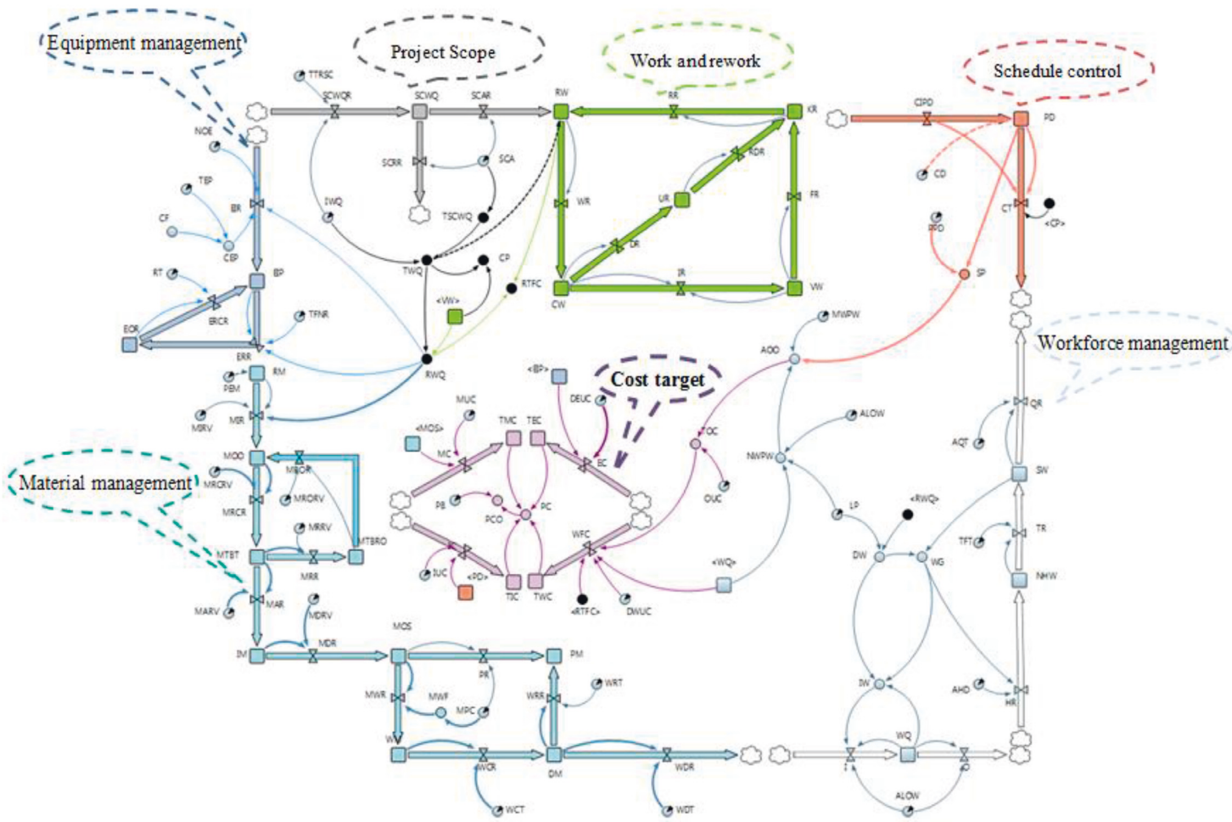

Figure 4: The architecture of the system dynamics model to be encapsulated.

conditions, operating efficiency, and the efficiency of the equipment driver. As a result, the theoretical equipment productivity is rectified using the correction factor in this subsystem. Furthermore, the suggested subsystem takes into account the necessity for maintenance over time, with the equipment repair rate and then the equipment recovery rate handling it.

(6) Schedule control subsystem: the anticipated and actual project durations are also included in this subsystem. When they are the same that means there will not be any limits on time. Otherwise, the project will be under scheduled pressure, which is defined as the difference between the actual project duration and the projected project duration as a percentage of the actual project duration.

(7) Cost target subsystem: the expected project cost may be calculated by adding up the material, equipment, labor, and indirect costs during the project. After that, the cost overrun may be calculated by comparing the planned and projected costs.

5.4. Model Variables. Stocks, rates, and converters are the three types of variables in a stock-flow diagram. Stock variables represent the condition of the system and create the data on which choices and actions are based [7], and they may be increased or decreased [35]. Rate variables are flows that describe the rate at which the stock is changing at any particular time; they either flow into or out of a stock, causing it to rise or decrease. Rate variables in this model are quantified and defined through a field study in which rates are collected from 15 case study projects located in Egypt. The decision-maker (model user) can decide whether to enter these rate variables' values himself or to use the defined variables recorded in the model database. Variables that are computed from other variables or constant variables are known as converter variables. The variables in the SD model are either input variables, output variables, or auxiliary variables. The input variables are the factors that have an impact on the cost performance. A cost overrun is the output variable in this suggested model. Auxiliary variables are the variables that are in between the input and output variables. Table 4 shows the important variables in this model and their simplified mathematical correlations (model equations) and the detailed full code for each variable is illustrated in Appendix A. (Note that the written equations are simplified for non-programmer readers, but the model equations were created using the AnyLogic® software, which utilizes the Java programming language.)

6. Discrete Event Simulation Modeling

A discrete system is one in which state variables change only at a limited number of time points [36]. The basis of this simulation approach is based on the notion of entities and resources, where the source is the entity's port and the sink is

Table 4: Main variables in the SD model.

Code	Subsystem	I/O/A type	Variable type	Equation
CP	Project scope	Auxiliary	Converter	(Verified works/total work quantity) ∗ 100
SCWQ	Project scope	Auxiliary	Stock	Integral (scope change rate – scope changes accepted rate, initial = 0)
RTFC	Project scope	Auxiliary	Converter	Remaining work quantity/work rate
RWQ	Project scope	Auxiliary	Converter	Total work quantity – (completion percentage ∗ total work quantity)
TWQ	Project scope	Auxiliary	Converter	Initial work quantity + scope changes work quantity
CW	Work and rework	Auxiliary	Stock	Integral (work rate – inspection rate – defect rate, initial = 0)
RW	Work and rework	Auxiliary	Stock	Integral (rework rate – work rate + scope change approval rate, initial = total work quantity)
VW	Work and rework	Auxiliary	Stock	Integral (inspection rate – failure rate, initial = 0)
WR	Work and rework	Input	Rate	Input
IM	Material management	Auxiliary	Stock	Integral (material approval rate – material delivery rate, initial = 0)
MAR	Material management	Auxiliary	Rate	Material to be tested/material approval time
MAT	Material management	Input	Converter	Input
CEP	Equipment management	Auxiliary	Converter	Theoretical equipment productivity ∗ correction factor ∗ number of equipment
EIP	Equipment management	Auxiliary	Stock	Integral (equipment recovery rate + equipment inflow rate – equipment repair rate, initial = number of equipment)
EIR	Equipment management	Auxiliary	Rate	Remaining work quantity/equipment production
DW	Workforce management	Auxiliary	Converter	Remaining work quantity/labor production
HR	Workforce management	Auxiliary	Rate	Workforce gap/average hiring delay
IW	Workforce management	Auxiliary	Converter	(Desired workforce – workforce quantity) ∗ workforce gap
I	Workforce management	Auxiliary	Rate	Increased workers + (workforce quantity/average length of work)
CID	Schedule control	Auxiliary	Rate	Current duration + remaining time for completion
PD	Schedule control	Input	Converter	Input
D	Schedule control	Auxiliary	Stock	Integral change in project duration, initial project duration)
SP	Schedule control	Auxiliary	Converter	(Project duration – planned project duration)/planned project duration
EC	Cost target	Auxiliary	Rate	Equipment in progress ∗ daily equipment unit cost ∗ (remaining time for completion
IC	Cost target	Auxiliary	Rate	Indirect unit cost ∗ project duration
MC	Cost target	Auxiliary	Rate	Material unit cost ∗ material on site
AC	Cost target	Auxiliary	Converter	Total equipment cost + total material cost + total indirect cost + total workforce cost
CO	Cost target	Auxiliary	Converter	Actual cost – planned cost
WC	Cost target	Auxiliary	Rate	Total overtime cost + (daily workforce unit cost ∗ workforce quantity ∗ remaining time for completion)

the final destination. Entities are inert things that travel through the workflow, share throughout the system, and can be processed (delayed, queued, seized, and split) but have no interactivity or attributes [37]. Each activity in a construction project is assigned a specified time and has relationships with its predecessors and successors. As shown in Figure 5, these relationships between activities can be one-to-one, one-to-many, or many-to-one, as in activity *A* to activity *B*, activity *B* to activity *C* and activity *D*, and activity *C* and activity *D* to activity *E*, respectively. The core aspects of the DES model, namely source, sink, split, and combine, may be used to express these interactions. A split can be used when an activity has more than one successor, and a combination can be used when an activity has two or more predecessors. The source indicates the start of the process; the sink represents the end of the process.

7. Hybrid Dynamic Model Development

Although, as shown in Figure 4, the system dynamics model used in this work is designed to capture the behavior of the residential system and its reaction to highly variables that impact cost performance. However, because the SD lacks the power to produce events on its own, it is unable to influence a discrete event. This problem may be solved by instructing each discrete element to keep an eye on the system dynamics variables and wait for a certain condition [38]. This study put that principle into practice by keeping an eye on a defined

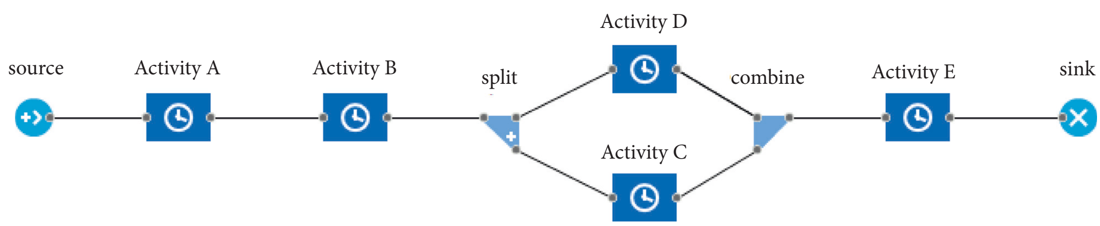

Figure 5: Representation of relationships between activities in DES.

variable in the system dynamics model. This variable is the completion percentage, and each discrete element (task) must keep an eye on the condition of obtaining a 100% completion percentage, which indicates that the work has been completed and the next task is about to begin.

The SD model is encapsulated within a DES event to form two independent modules, namely "Task Module" and "Continuity Module," as shown in Figure 6. The "Task Module" contains the attributes and behavior of the project's many tasks. To represent each task in the project, many instances of the "Task Module" were constructed, and then all instances were connected to the task's network. On the other hand, the "Continuity Module" incorporates the attributes and behavior of the system that continually influences the project cost while doing activities. The "Task Module" and the "Continuity Module" are linked to a database that stores the various data associated with each task. As a result, according to the database, all the work can be extracted from the "Task Module" and "Continuity Module," considerably boosting the model's efficiency.

The source generates an entity at the start of the encapsulation process; then the entity begins to pass through the "Task Module"; the SD model then operates; and an event-watcher begins to watch the "Task Module," once the task is completed, that event gives an alarm to notify the source to create a new entity and begin the next task (or next tasks if there are available ready parallel tasks to start). Simultaneously, the "Continuity Module" is operating in the background, keeping track of the cumulative continuous expenses as the activities are completed. Eventually, all of the entities created by source will flow into sink.

8. Case Study

The suggested system dynamics model is used for a residential construction project in Al Alamein, Egypt, to test and simulate it. This project was chosen because the information supplied was quite thorough, and hence, the data needed for the suggested model was available. Furthermore, because the project's complexity was moderate, model issues could be recognized. The Al Alamein Residence building is situated next to the old Al Alamein Hotel. It consists of three buildings with a total of six stories (basement level, garden level, entry-level, first, second, and third levels) plus a parking level on the basement level executed in two phases: the first phase includes the two interconnected buildings, while the third building is planned to be in the second phase. The project's first phase took 360 calendar days to be completed, including mobilization and handover periods, with a total contract sum of EGP 400, 473, 350 EGP and an excess cost of EGP 67, 120, 760 EGP, representing a 16.8% cost overrun. For modeling, testing, and application, building *B*1 is chosen. Figure 7 depicts the activity on the node for the building's substructure works, and the description of each task is shown in Table 5.

8.1. Model Validation

8.1. Model Validation. Model testing is a multidimensional iterative process in which the simulation output is compared to the real system to investigate discrepancies. After that, model parameters are updated to correct inconsistencies, and the model is resimulated. The technique is continued until the model structure fulfills the model behavior requirements [39]. Several tests have been devised to discover flaws in the system's dynamic models, which may subsequently be improved. These tests are divided into two categories: structural tests, and behavior tests. The model tests that were applied to the proposed model will be explained in the next section.

8.1.1. Model Structure Tests. Four direct structural tests, based on Barlas [40], were applied to this model: structure confirmation, parameter confirmation, boundary adequacy, and dimensional consistency.

(1) The structure confirmation test compares the model's causality and feedback to real-world relationships. By comparing the interrelationships and polarity of variables with the existing literature, the causal loop diagrams were thoroughly evaluated and validated. Following that, the schematics were put to the test in a series of workshops, and all of the functions were validated by specialists. As a result, the structure confirmation test is satisfied by the system dynamics model.

(2) The parameter confirmation test examines the model's constant parameters based on conceptual and numerical confirmation. To obtain conceptual confirmation, the model's parameters should match the elements of the actual system. The precision of model parameters is required for numerical confirmation completion. The SD model satisfies the criteria of the parameter confirmation test since each parameter in the system dynamics model is derived from a simple building project.

(3) The boundary adequacy test assesses if the model incorporates all of the relevant aspects that impact

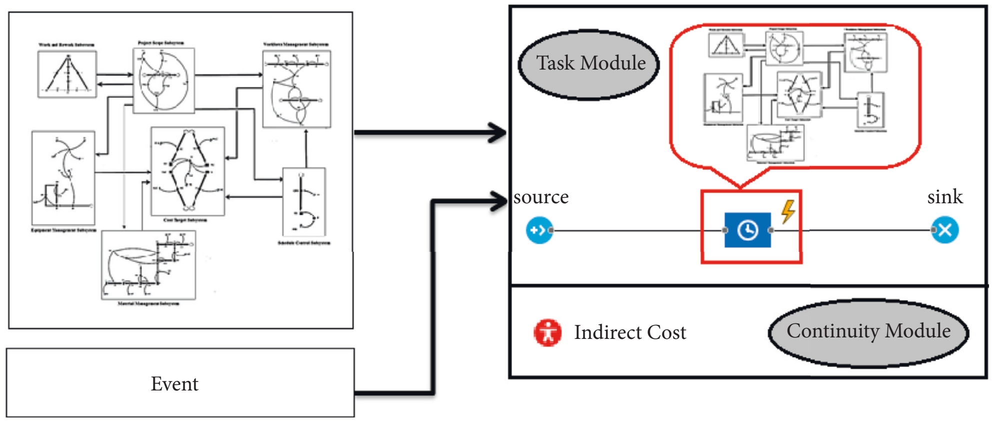

Figure 6: Representation of encapsulation process.

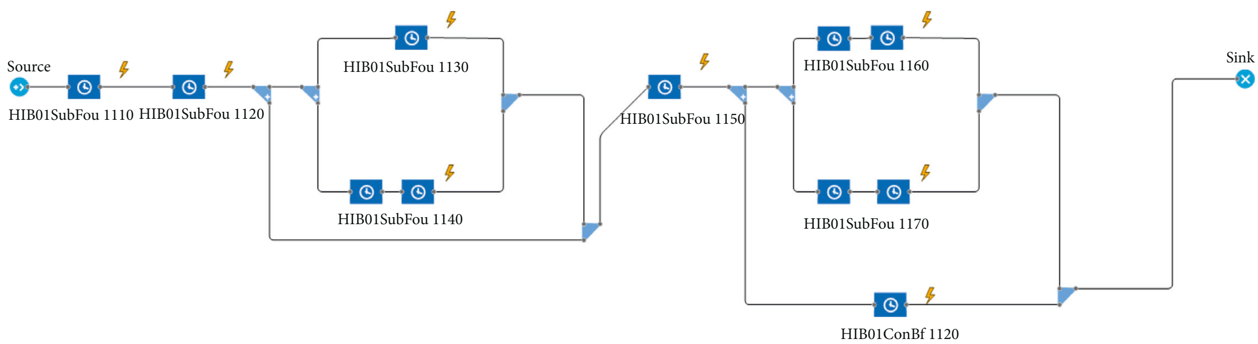

Figure 7: AON network for substructure works of building $B1$.

the study goals. Each variable in this research was handpicked from a variety of sources, including a literature review, interviews, archival documents, and field notes. Within the model boundaries, the endogenous, exogenous, and excluded variables were previously discussed in Figure 3.

(4) The dimensional consistency test was carried out by examining the right- and left-hand sides of each equation for consistency. The test is carried out using the AnyLogic® software's "Check System Dynamics Units," and no issues are discovered.

8.1.2. Model Behavior Testing. The model behavior test is used to determine how well the model can simulate real-world behavior. An equation can be used to represent the error rate (2) [21].

$$e_i = \frac{(\hat{y}_i - y_i)}{y_i}, \quad (2)$$

where e_i indicates the error rate between the actual cost and the cost estimated by the model for the task (i), y_i is the actual cost of task i, and $\hat{y}_i$ is the model cost of task i.

Several tasks from the case study project have been chosen as indicators for estimating the SD model's error rate. Table 5 shows the findings of the error rate calculation. The tasks had an average error rate of 2.07%. These findings suggest that the suggested model satisfies the model behavior test's requirements.

8.2. Simulation Results. This section describes a dynamic simulation technique that allows decision-makers to simulate nonlinear and complex interactions between parameters influencing the project cost in residential projects. The input data for the base run of the model developed in this study were obtained from the following tasks from building $B1$: formwork for footings and raft "H1-B01-SUB-FOU-1130," steel reinforcement for footings and raft "H1-B01-SUB-FOU-1140," and pouring footing and raft "H1-B01-SUB-FOU-1150." The desired reinforced concrete quantity was 1,854.66 m^3.

The DES system is encapsulated in a class to formulate the task module; multiple instances are created from this task and connected to represent the task flow for the project (task network); and the relationships and dependencies are defined for each task to be performed according to the predefined sequence and conditions as task "H1-B01-SUB-FOU-1150" depends on the completion of tasks "H1-B01-SUB-FOU-1130" and "H1-B01-SUB-FOU-1140," while tasks "H1-B01-SUB-FOU-1130" and "H1-B01-SUB-FOU-1140" can run in parallel as illustrated in Figure 7.

The graphs in Figures 8 and 9 represent the progress of multiple mentioned tasks that depend on each other. During the simulation, an entity, which is a passive element, flows

Table 5: The error rate results.

No.	Task ID	Description	Actual cost (EGP)	Model cost (EGP)	Error rate
1	H1-B01-SUB-FOU-1110	Formwork for plain concrete footing below raft, RW, and footings	161,202	156,108	−3.16%
2	H1-B01-SUB-FOU-1120	Plain concrete footing below raft, RW, and footings	187,291	185,568	−0.92%
3	H1-B01-SUB-FOU-1130	Formwork for footings and raft	1,071,888	1,034,480	−3.49%
4	H1-B01-SUB-FOU-1140	Steel reinforcement for footings and raft	2,160,879	2,120,892	−1.85%
5	H1-B01-SUB-FOU-1150	Pouring footings and raft	1,505,060	1,468,478	−2.43%
6	H1-B01-SUB-FOU-1160	Backfilling works for footings and raft	29,210	29,189	−0.07%
7	H1-B01-SUB-FOU-1170	Damp-proofing for foundation and RW	35,761	34,520	−3.47%
8	H1-B01-SUB-SOG-1140	Waterproofing for brickworks under SOG	128,447	124,106	−3.38%
9	H1-B01-SUB-SOG-1150	Backfilling works under the slab on grade	162,773	162,626	−0.09%
10	H1-B01-SUB-SOG-1160	MEP under slab on grade	116,619	115,825	−0.68%
11	H1-B01-SUB-SOG-1170	Brickworks under the slab on grade	79,550	78,659	−1.12%
12	H1-B01-SUB-SOG-1180	Blinding below slab on grade	151,484	150,696	−0.52%
13	H1-B01-SUB-SOG-1200	Polyethylene sheet below slab on grade	48,962	48,428	−1.09%
14	H1-B01-SUB-SOG-1190	Steel reinforcement and pouring slab on grade	849,845	847,125	−0.32%
15	H1-B01-CON-BF-1120	Basement floor columns, cores, RW, and shear walls	950,815	934,651	−1.70%
16	H1-B01-CON-BF-1130	Formwork for basement floor slab	428,331	412,568	−3.68%
17	H1-B01-CON-BF-1140	Steel reinforcement for basement floor slab	1,087,830	1,070,098	−1.63%
18	H1-B01-CON-BF-1170	Installation of embedded conduit and boxes in concrete slab # GF	5,012	5,000	−0.24%
19	H1-B01-CON-BF-1160	Pouring basement floor slab	543,915	531,350	−2.31%
20	H1-B01-FN-BF-100	Block work for basement floor	498,262	493,329	−0.99%
21	H1-B01-FN-BF-110	Plastering preparation works for basement floor	35,039	33,546	−4.26%
22	H1-B01-FN-BF-120	Screed works for basement floor	39,163	37,929	−3.15%
23	H1-B01-FN-BF-130	Insulation works for basement floor	71,690	69,152	−3.54%
24	H1-B01-FN-BF-140	Plastering works for basement floor	277,640	266,478	−4.02%
25	H1-B01-FN-BF-150	Installation of ceramic/porcelain wall tiles for basement floor	119,520	116,102	−2.86%
26	H1-B01-FN-BF-160	Installation of ceramic/porcelain floor tiles for basement floor	71,214	69,675	−2.16%
27	H1-B01-FN-BF-170	Installation of doors for basement floor	100,329	99,084	−1.24%
28	H1-B01-FN-BF-180	Gypsum board works for ceiling for basement floor	5,532	5,482	-0.90%
29	H1-B01-FN-BF-190	Paint preparation and prime coat for basement floor	10,352	9,862	−4.73%

from task “H1-B01-SUB-FOU-1120” to be split, allowing the system dynamics in the task module for activities “H1-B01-SUB-FOU-1130” and “H1-B01-SUB-FOU-1140” to start and work in a parallel manner until reaching the 100% completion percentage as per planned finish to finish with 1-day lag relationship; then both entities from the two tasks are combined to be one entity flows to the task “H1-B01-SUB-FOU-1150” allowing the system dynamics in the task module for this activity to start as per planned finish to start relationships as illustrated in Figure 8.

On the other hand, entering the task module to track the behavior of the aforementioned tasks via the work-rework subsystem reveals that the stock of remaining works gradually decreases from the total work quantity until all

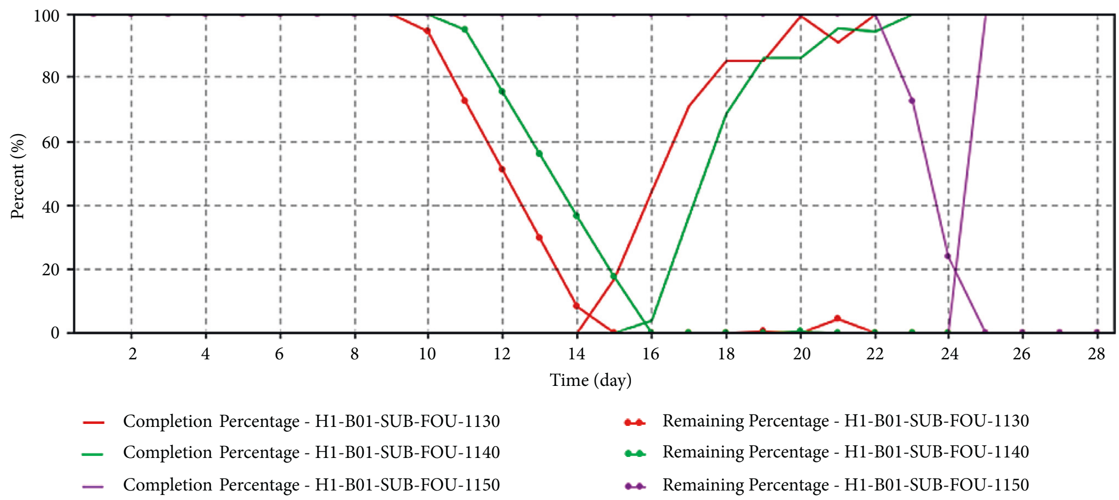

Figure 8: The completion process for the DES tasks.

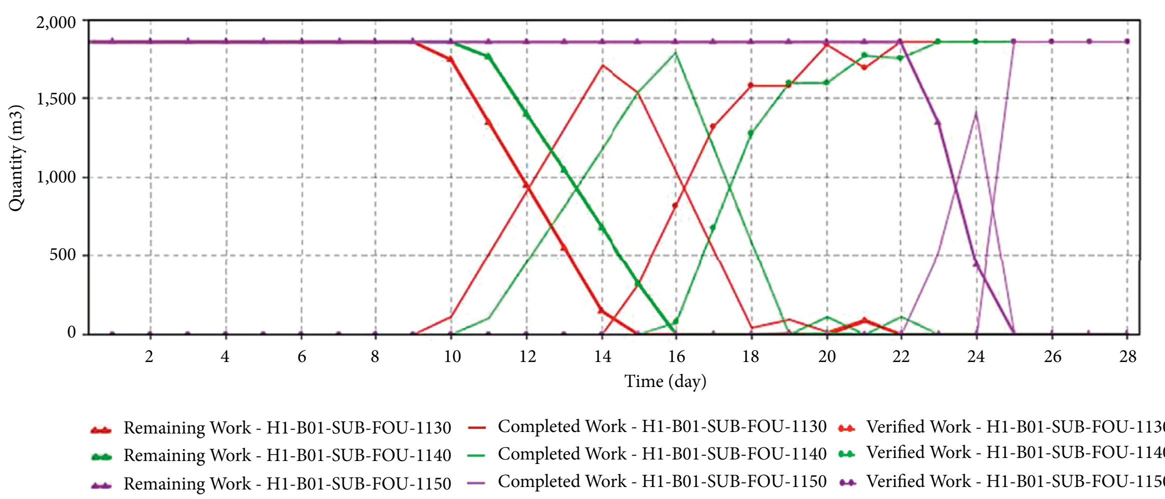

Figure 9: The behavior of the work and rework process.

remaining works are completed at the end of the task duration, whereas the stock of verified works grows in an *S*-shaped pattern. The completed works stock is initially empty until the task is completed and inspected by the contractor's quality control team, at which point the stock value starts to decline as accepted work is transferred to the verified stock, while undetected rework and known rework stocks gradually increase during the inspection. The completion percentage remains constant at zero until the job is done and confirmed by the consultant's team, except for the remaining work quantity percentage, which steadily lowers until it reaches zero. Figure 9 depicts this work-rework cycle.

Figure 10 describes the material management cycle behavior for tasks "H1-B01-SUB-FOU-1130," "H1-B01-SUB-FOU-1140," and "H1-B01-SUB-FOU-1150." The material for shuttering formwork is requested by the 9th project day; then the material is tested; and the approved material is delivered to the site to start the task, converting the timber into productive formwork and waste material. This waste later can be classified into items that may be reused, which flow to productive material stock via the waste reuse rate, or disposal materials, which remain in disposal material stock. Meanwhile, by the 10th project day, the steel required for reinforcing in the task "H1-B01-SUB-FOU-1140" start to be requested and tested; then the approved material is delivered to the site to start the task, converting the steel into productive steel and steel waste. By day 22 of the project, the concrete can be requested; the tests for the green concrete have been conducted; and then the approved green concrete is been poured.

9. Effect of the Unexpected Global Events on Cost Performance

As mentioned above, the case study project consists of three buildings executed in two phases; the first phase include two interconnected buildings, while the third building is planned to be in the second phase. The two phases have the same construction conditions except that in the second phase, the Russian-Ukrainian war broke out, which led to a shortage of raw materials in addition to an increase in their prices. To explain this influence on cost performance the material management process in activity "H1-B01-SUB-FOU-1140"

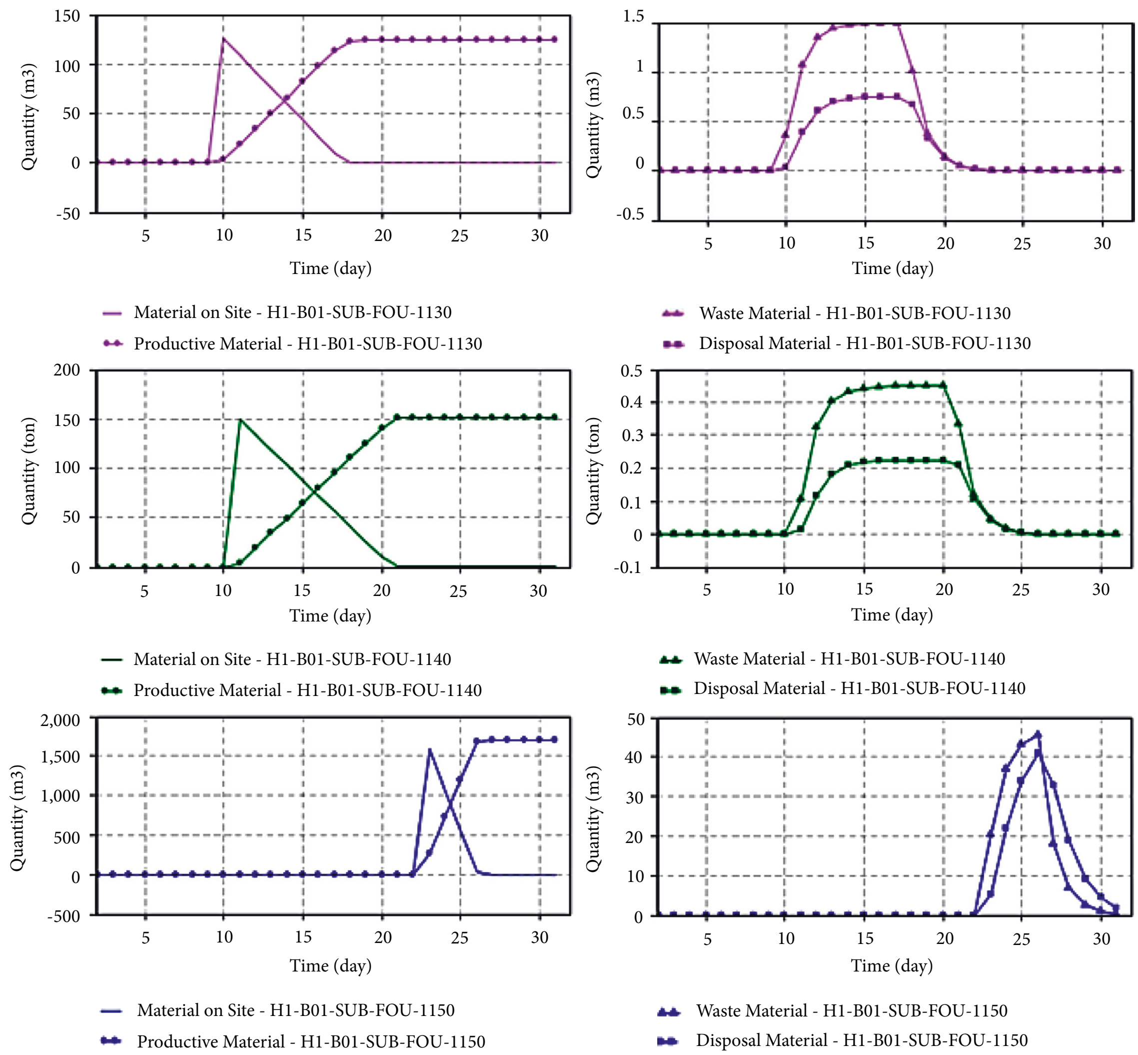

Figure 10: Behavior of the material-resources management process.

was compared with its counterpart in the second phase with the stability of all conditions as illustrated in Figure 11.

10. Effect of the Determined Critical Risks on Cost Performance

Following the cost risk identification section's discovery of the most important risks impacting cost performance, a Delphi technique was used to estimate the parameters of the best and worst scenarios for the identified most essential cost risks. A questionnaire was created as a supplement to collect the two values listed above for each identified risk. The distribution of expert replies was evaluated once all of the questionnaires were gathered, and the stop condition was that the absolute deviation was within 5% variation of the median.

Each expert received an anonymous summary of the previous round's experts' responses and their reasoning for their answers after each round, and experts were encouraged to alter their answers if wanted. As indicated in Table 6, the best and worst scenarios for the substructure works from the case study project were applied to the hybrid SD-DES model.

The percentage of the increased cost is defined as the proportion of project costs that are lost or improved as compared to the costs of the probable scenario when a certain parameter's value differs from the likely scenario value. According to the findings, the highest cost performance regression in residential projects is caused by unanticipated changes in material costs.

11. Discussion

Based on the results of this model, considering the costs of failures, rework, scope changes, workforce re-hiring, repairing equipment, and material reordering, in addition to, considering their effect on project duration results in more direct and indirect costs, and the total project cost can be determined with little unexpected costs; thereby the total cost overrun can be eliminated or reduced.

The simulation results in the developed system dynamics model described the dynamics of the rework cycle and its effect on time and cost. The decision-makers may miss this cycle effects while using traditional methods. This result is

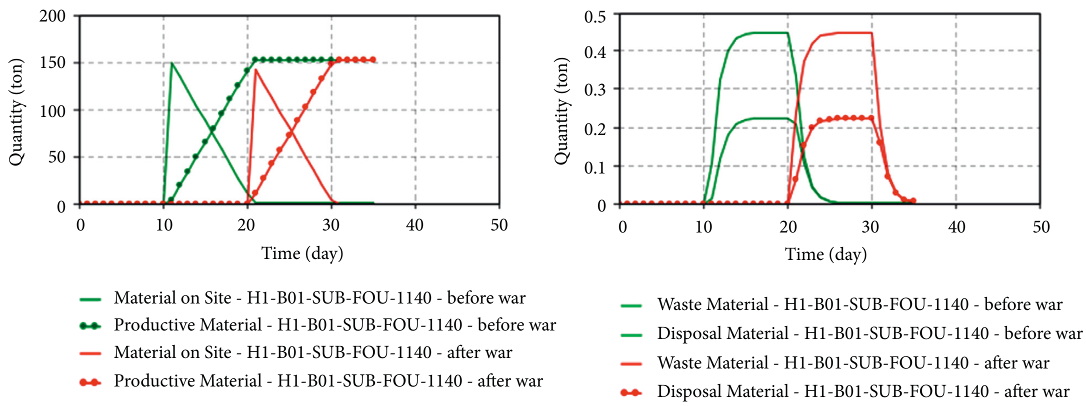

Figure 11: Effect of Russian-Ukrainian war on material-resources management process.

Table 6: Cost performance under critical risks.

No.	Description	Scenario		Cost performance		
		Best	Worst	Min cost (EGP)	Max cost (EGP)	% of increased cost
—	Base run	—	—	7,537,727	7,537,727	—
1	Unexpected fluctuation in material prices	−50% of MUC	50% of MUC	5,569,545	8,902,188	44%
2	Change requests during construction	−25% of IW	25% of IW	6,783,954	8,656,963	25%
3	Change in project duration	0% of PD	100% of PD	7,130,794	7907,928	10%
4	Shortage of equipment	−50% of NOE	50% of NOE	7,394,690	7,734,562	5%
5	Rework due to mistakes	−50% of FR	50% of FR	7,362,439	7,758,891	5%

consistent with the research of [34], which investigated an infrastructure project (a tunnel with a length of 3,875 m) using a system dynamics approach that contains six subsystems (scope, progress and rework, resources, performance, cost breakdown, and objective control). Their results show that during the simulation, work remaining decreases gradually, while work accomplished and known rework have *S*-shaped growth, while the undiscovered rework seems to have overshoot and collapse. The current study covers the gap of investigating a single task considering the progress of multiple tasks, namely "formwork for footings and raft," "steel reinforcement for footings and raft," and "pouring footings and raft" that depend on each other.

Also, the results show that the risk of a shortage of skillful construction labor would significantly affect the project schedule and consequently cost. This result is consistent with the research of [15] as their research developed a system dynamics model to investigate the risk effects on a project schedule. The model contains eight essential elements: construction tasks, labor quantity, employment of labor, worker productivity, project progress, project reworks, project schedule, and the schedule adjustment scheme. To overcome this risk, the proposed model in this research takes into consideration the needed time for the newly hired workforce to be trained and certified to ensure that they are aware of the procedures and risks concerned as described in Figure 4.

As per the analysis result, the shortage of productive equipment has a significant effect on cost performance, and the model described the correlation between the work-rework cycle in addition to the equipment management cycle (as described in Figure 4), which matches the result of Oleghe and Salonitis [17] research, which stated that the most important is ensuring complete compliance with routine and scheduled maintenance tasks, as well as coordinating the latter to correspond with the rate of machine defect creation.

The results present the effect of the Russian-Ukrainian war on the construction industry that consists of the expectations of the research of Shah and Majeed [41] that stated that "This war will not only drive up the prices of raw materials, but it will also cause a shortage of exported goods, which will directly affect ordinary people."

12. Conclusions

This work suggested a hybrid SD-DES model to address the shortcomings of prior risk evaluation studies, resulting in an efficient and practical tool for measuring the influence of significant risks on residential project cost performance. Failures, rework, scope modifications, workforce rehiring, equipment maintenance, and material reordering were all factored into the model, as well as their impact on project length. Direct costs were calculated using the task module, while indirect costs were calculated using the continuity module. Total project costs may be calculated with few unexpected charges, reducing or eliminating total cost overruns.

The influencing cost risks were first identified in the literature, followed by a questionnaire survey and data analysis using the importance index method. Finally, the developed model was bounded, and causal relationships were formed in a causal loop diagram, which was followed by developing mathematical equations using the stock-flow diagram. To allow a better understanding of cost performance from a strategic level, the entire residential system was divided into seven subsystems: project scope subsystem, work and rework subsystem, material management subsystem, workforce management subsystem, equipment management subsystem, schedule control subsystem, and cost target subsystem. As a consequence, the SD model was enclosed into an event in DES, which resulted in two modules: task and continuity.

The hybrid model was tested using the Al Alamein Residence building in Egypt, and then a simulation study was carried out to describe the dynamics of the rework cycle and its influence on time and cost, which decision-makers may overlook using standard approaches.

After that, a risk impact analysis was carried out. The unanticipated variation in material costs produces the greatest cost performance regression in residential projects, according to this data. This consequence is visible, particularly in light of the Russia-Ukraine conflict, which has had a considerable impact on the supply of raw materials for building as well as their high pricing.

12.1. Limitations and Further Recommendations. Although the proposed hybrid dynamics model supports the decision-making process by analyzing the overall cost risks and increasing the understanding of the behavior of the construction projects, especially residential projects from strategic as well as operational levels, the proposed model still has limitations that should be addressed for further development. The model only considers the scenario where one risk occurs while multirisk scenarios affecting the cost performance in the residential projects should be addressed. Moreover, the model was applied to a residential project only it is not clear if the model can be applied to an infrastructure project or mega projects.

Abbreviations

AAOSC: Accepted amount of scope changes
AHD: Average hiring delay
ALOW: Average length of work
AOO: Amount of overtime
AQT: Average quitting time
CD: Current duration
CEP: Corrected equipment productivity
CF: Correction factor
CIPD: Change in project duration
CP: Completion percentage
CW: Completed works
DEUC: Daily equipment unit cost
DM: Disposal materials
DR: Defect rate
DW: Desired workforce
DWUC: Daily workforce unit cost
EC: Equipment cost
EDE: Equipment driver efficiency
EIP: Equipment in progress
EIR: Equipment inflow rate
EL: Equipment lifetime
EOR: Equipment on repair
ERCR: Equipment recovery rate
ERR: Equipment repair rate
EUC: Equipment unit cost
FR: Failure rate
HR: Hiring rate
I: Inflow
IC: Indirect cost
IM: Inspected material
IR: Inspection rate
IUC: Indirect unit cost
IW: Increased workers
IWQ: Initial work quantity
KR: Known rework
LWR: Labor production
MAR: Material approval rate
MAT: Material approval time
MC: Material cost
MDR: Material delivery rate
MDT: Material delivery time
MIR: Material inflow rate
MOO: Material on order
MOR: Material ordering rate
MOS: Material on site
MOT: Material ordering time
MPC: Material per completion
MRT: Material rejection rate
MTBT: Material to be tested
MWF: Material waste fraction
MWPW: Max work per week
MWR: Material wastage rate
NHW: Newly hired workforce
NOE: Number of equipment
NWPW: Normal work per week.
PD: Project duration
PEM: Planned expected material
PM: Productive material
PPD: Planned project duration
PR: Productive rate
PSC: Project scope changes
QT: Quit rate
RDR: Rework detection rate
RM: Required material
RR: Rework rate
RT: Recovery time
RTFC: Remaining time for completion
RW: Remaining works
RWQ: Remaining work quantity
SCA: Scope changes approval
SCAR: Scope changes accepted rate
SCP: Scope changes percentage
SCR: Scope changes rate
SCWQ: Scope changes work quantity
SP: Schedule pressure
SW: Skilled workforce
TEC: Total equipment cost
TEP: Theoretical equipment productivity
TFNR: Time for needing repair
TFT: Time for training

TIC: Total indirect cost
TMC: Total material cost
TOC: Total overtime cost
TR: Training rate
TTASC: Time to accept scope changes
TTRSC: Time to request scope changes
TTSPSC: Time to start performing scope changes
TWC: Total workforce cost
TWQ: Total work quantity
UR: Undetected rework
VW: Verified works
WC: Weather conditions
WC: Workforce cost
WCR: Waste classification rate
WCT: Waste classification time
WDR: Waste disposal rate
WDT: Waste disposal time
WE: Working efficiency
WG: Workforce gap
WM: Waste material
WQ: Workforce quantity
WR: Work rate
WRR: Waste reuse rate
WRT: Waste reuse time

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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