



# Article Integrated Agent-Based Simulation and Game Theory Decision Support Framework for Cash Flow and Payment Management in Construction Projects

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Abstract: Effective cash flow management has become crucial for projects and stakeholders given the wide payment-related problems and financial risks encountered in the construction industry worldwide. Previous studies mostly addressed cash flow and payments from the perspective of a specific stakeholder, resulting in an imbalanced cash flow management culture that is further intensified by the power asymmetry of the top-down payment decision-making process. This research proposes an adaptive decision support framework for evaluating and negotiating payment options in construction projects while incorporating the individual and collective financial roles of stakeholders. The framework is comprised of three modules for data acquisition, payment simulation, analysis, and negotiation, as well as decision support. It integrates agent-based simulation, data envelopment analysis, and game theory for a multi-level study of project performance while capturing the driving forces of stakeholders in payment negotiations. A case study project is used to demonstrate the framework implementation under varying payment conditions and interest rates. The results provide quantitative profiles of stakeholders to identify incurred charges, balanced payment conditions, and suitable compensation. Finally, the framework can be utilized by stakeholders and jurisdictions to move towards enhanced contractual arrangements that alleviate economic and financial risks with the informed collaboration of its entities.

**Keywords:** construction project management; stakeholder management and empowerment; payment process; cash flow analysis; economic and financial risks; agent-based simulation; data envelopment analysis; payment negotiation; game theory; decision support system

# 1. Introduction

The recent disturbances of the global economic conditions have raised wide concerns regarding the high inflation, rising interest rates, supply chain disruptions, labor shortages, and volatile energy prices. Such conditions can be challenging for the construction industry given its complex and dynamic nature in addition to the persistent inefficiencies, cash flow difficulties, and problematic payment conditions often encountered by stakeholders (owners, contractors, and subcontractors). Therefore, it has become crucial to assess and incorporate such factors in the effective planning and management of construction projects.

Economic instability, poor cash flow management, and insufficient financial resources can result in financial problems that could affect sustainable construction project delivery [1,2]. Cash is the most important resource for preserving efficient day-to-day construction activities [3]. During project progress, cash shortages result in delays, penalties, and loss of opportunities which are reflected in the financial health of projects and organizations as project failure and business bankruptcy [4]. Accordingly, effective cash management is of central importance for construction companies to identify potential financial problems and successfully deliver high performing projects. Effective cash flow management involves



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). forecasting, planning, monitoring, and controlling cash disbursements and receipts at all phases of the construction process and over the life of a business [5,6].

A major factor leading to the successful completion of construction projects is the practice of efficient and timely payment. Unfortunately, the dynamic nature of construction projects combined with the large number of stakeholders involved complicates and lengthens the payment process, making it a prevalent source of concern across the world [7,8]. Common payment problems often arise in the form of delayed payment, nonpayment, or underpayment of amounts certified [7]. This may be attributed to conflicts over work performance, inadequate documentation, financing issues, or other related causes [1]. In addition, the adversarial relationship and asymmetric power balance among stakeholders may result in upper-tier stakeholders adopting unfair contractual payment provisions for their interest and financial advantage [1,9]. This transfers financial risks to other stakeholders down the payment chain, putting them in involuntary financing roles [10]. However, not all stakeholders are empowered to negotiate such conditions nor have the financial capacity to withstand them. Such poor payment practices result in adverse impacts that cascade down the construction payment chain and affect project performance, stakeholder financial stability, employment, productivity, and investment [7,11].

Previous studies have widely investigated cash flow management and forecasting techniques [12]. However, they mostly focused on the analysis component of cash flow from the perspective of a specific stakeholder with limited incorporation of the analysis results in a joint decision-making process. In addition, prompt payment legislation has been enacted in various global jurisdictions to alleviate the financial risks encountered in the construction industry [8]. Nevertheless, construction payment problems and imbalanced payment practices still persist, affecting the performance of projects and stakeholders. This requires further investigation of the impacts and effectiveness of such efforts to better address the problems and offer effective and applicable mitigative approaches.

The aim of this research is to develop an analysis and decision support framework for cash flow and payment management in construction projects for various stakeholders (owner, contractor, and subcontractors). The framework integrates agent-based modeling and simulation with game theory to incorporate the individual and collective characteristics of stakeholders in analyzing the cash flow and payment system as well as the joint decision-making process. It can be used for the comprehensive analysis of project performance and stakeholders' financial stability under varying payment policies, interest rates, resource availability, financing conditions, contractual arrangements, and external factors. The findings are then used as the basis for negotiating contractual and payment terms among stakeholders for the improved financial performance of project and stakeholders.

## 2. Literature Review

This section presents a brief literature review of the research problem, providing an overview of the interrelated areas of cash flow management and construction payment-related problems.

## 2.1. Cash Flow Management in Construction Projects

Each construction project has its own cash cycle that consists of cash outflows and inflows [3]. For the cash outflows, a detailed quantity take-off and cost estimation facilitates the quantification of the monetary resource requirements for the completion of the project. As for the cash inflows, an efficient payment mechanism may benefit owners, contractors, and subcontractors in enhancing productivity and achieving corporate financial objectives [13]. Another aspect of cash flow analysis and management is the incorporation of risks and uncertainties due to project-related problems and changes in the business environment which may consequently affect the financial performance of construction projects [14].

There are a myriad of factors that affect cash flow including project schedule, activity costs, work productivity, contract terms, payment lag and delays, retention, credit arrangement, financial risks, and loan repayments, in addition to macroeconomic factors such

as tax policy, inflation, and interest rate [3,7,15]. Accordingly, numerous techniques were developed in the literature for cash flow management and forecasting with varying levels of accuracy and detail, as reviewed in [12].

Several researchers present cash flow analysis frameworks using building information modeling (BIM) for their accurate quantity take-off and cost estimation [16–18]. Such studies are mostly based on contractors' expected expenditure with limited consideration of stochastic inflow aspects as income patterns and payment delays. Other approaches for project cash outflow analysis include moving weights of cost categories [3], statistical models using algebraic formulations and polynomial regressions [19], stochastic S-curves [20], fuzzy modelling of durations and/or costs [14], Bayesian belief networks [21], stratified multi-criteria decision-making [22], artificial neural network [23], and heuristics [24]. Nevertheless, the majority of such studies follow contractual payment terms which may not allow contractors and subcontractors to effectively plan their work and financial arrangements based on the uncertainties of the actual payment practices. The models also address cash flow management from the viewpoint of one party, mostly the contractor, with limited consideration of other parties that affect the financial operations.

Research studies have also addressed contractors' cash flow uncertainties related to owner payment practices [25]. Carmichael and Balatbat [26] presented a Markov Chain model for the contractor's internal analysis of the likelihood of late and incomplete payments in an uncertain payment environment. Tran and Carmichael [25] presented a method for cash flow and present value analysis under uncertainty based on an owner's payment history. Moreover, Hoseini et al. [27] developed a stochastic simulation-based cash flow framework using Monte Carlo to predict the maximum finance required by contractors and the financing cost incurred under delayed payment. This framework was extended by Andalib et al. [15] to include the owners' payment history and intertemporal correlation between successive progress payments.

Additional efforts have focused on developing cash flow simulation models using system dynamics. For instance, Cui et al. [5] presented a model for evaluating the impacts of cash policies and project operations on project cash flow. Hou et al. [28] proposed a model to explore the behavior of project cash flow system and profitability under different payment problems and conditions. Another study by Xie et al. [29] modeled the impacts of delayed payment on the progress of construction projects and concluded that shortening the payment period for contractors and subcontractors will accelerate the flow of funds and ensure smooth progress. Furthermore, Dabirian et al. [6] presented a model to analyze the effects of financial policies related to owners, financial institutions, labor, and suppliers on contractors' cash flow. However, system dynamics is a top-down modeling approach that represents system components and their interactions at high aggregation level without considering the heterogeneity of distinctive entities [30].

The payment negotiation process is also addressed in the literature. Dayanand and Padman [31] developed decision tools based on mixed-integer linear programming models to support owners in determining the optimal payment schedule during the contract negotiation process. Moreover, Jiang [13] presented a multi-period dynamic model for negotiating financial terms on the project level with the objective of maximizing the final cash balance. Alavipour and Arditi [32] proposed a model that calculates the bid price using an optimized financing cost and schedule based on different financing alternatives. Elazouni et al. [9] presented a genetic algorithm model for contractors to negotiate offering prompt payments in return of subsidized prices from subcontractors. Nevertheless, such studies do not facilitate a collaborative and joint decision-making process that accounts for the various stakeholders involved in a project along the payment chain.

## 2.2. Construction Payment-Related Problems

Construction payments typically flow from the owner to the main contractor and then to various subcontractors, sub-subcontractors, suppliers, and vendors. Construction payment problems often arise in the form of delayed payment, nonpayment, or underpayment of amounts certified, causing construction businesses to suffer from cash flow problems [7,11]. They can be attributed to issues with the valuation of final accounts, late release of retention money, valuation of variations, following erroneous payment procedure, and withholding amounts without contractual basis [1].

Decisions of late payment and nonpayment reflect the adversarial relationships and power asymmetry among stakeholders in the construction industry [33]. Contractors are willing to accept unfair allocation of payment risks, giving the owner superior bargaining power [11]. The same applies to subcontractors who accept payment problems and poor practices as being a part of doing business and often believe that they cannot influence payment terms [10]. However, stakeholders at the top of the payment chain are mostly capital-intensive enterprises that can easily acquire funds, while most subcontractors at the end of the chain are labor-intensive firms with limited funds and risk resistance [10].

Construction payment problems are prevalent and have been a source of concern in construction industries across the world [7]. Several studies have explored payment problems in different countries and from different perspectives [1,7,10,11,33,34]. However, the majority of these studies are based on questionnaire surveys with the objective of identifying the causes, impacts, and potential solution strategies for construction payment problems. Other studies explored the use of developing technological advances such as automated progress-tracking techniques, blockchain, and smart contracts for an efficient, transparent, secure, and automated payment process [35]. Such studies may partially address the problem of poor payment practices. However, the issues of unfair payment provisions and contractual negotiation require further investigation.

The implications of payment problems and disputes motivated the introduction of prompt payment legislation in jurisdictions worldwide including in the United States, the United Kingdom, New Zealand, Singapore, Ireland, Malaysia, and Canada. Such legislation aims to address the timeliness of payments and increase cash flow by specifying aspects regarding payment triggers, payment period, basis for withholding payments, remedies for nonpayment, dispute resolution mechanisms (if any), and other aspects that shape the payment system and stakeholders' interactions. Dorrah and McCabe [8] presented a critical review of various prompt payment legislation and investigated some of the challenges that may hinder their effective implementation.

#### 2.3. Research Gaps

Based on the presented literature review on cash flow and construction paymentrelated problems, the main research gaps that need to be addressed are:

- The majority of cash flow forecasting models do not study the cash outflow and inflow simultaneously with the same level of detail [12]. This may result in some deficiencies in the cash flow management process.
- The cash flow and payment process are mostly studied from the single perspective of stakeholders while focusing on specific dimensions such as the payment timing [15]. There is a need for a comprehensive approach that accounts for the interacting payment dimensions of the various stakeholders involved.
- The top-down approach of setting payment arrangements results in the limited contribution of lower-tier stakeholders [10]. Upper tiers therefore need to study their payment practices under economic fluctuations. This requires a bottom-up analysis of stakeholders along the payment chain to support a balanced and joint decision-making process.
- The majority of studies on payment problems use qualitative analysis approaches which may not fully capture the effects of the problem or assess the proposed mitigative actions [1,8]. Therefore, it is imperative to develop a quantitative model with analysis metrics to analyze the performance of projects and stakeholders.
- The financial planning is mostly performed during early project stages with limited consideration of changing conditions that entail continuous adjustment throughout the project lifecycle [12]. This requires an adaptive system that effectively utilizes technological advances in enhancing various areas of cash flow and payment management.

The main objective of this research is to develop an adaptive decision support framework for evaluating, managing, and negotiating payment options and decisions in construction projects. The aim is to continuously implement this framework during planning and construction stages to develop robust cash flow and payment arrangements that account for possible changes throughout the project progress. This objective is achieved through the following sub-objectives:

- Payment policy and financial risks: simulate and analyze various payment arrangements and decisions based on varying interest rates and stakeholders' financial performance to investigate opportunities for improvement.
- Contractual and project conditions: assess the impacts of contractual provisions, project characteristics, and external factors on projects and stakeholders' performance.
- Multi-level analysis: model and study the project components on multiple levels to account for the individual characteristics and features of stakeholders, work items, and resources while studying the collective performance of projects.
- Negotiation and joint decision-making strategies: set the basis for balanced negotiation setting to reach mutually rewarding agreements that address the individual and collective objectives of stakeholders, alleviate financial stresses, and improve project performance.

The structure of the framework should allow the individual representation of stakeholders along with their conflicting objectives and interactions in analyzing the payment and joint decision-making processes. For this purpose, the proposed framework integrates agent-based simulation and game theory for a multi-level study of the performance of projects, stakeholders, work items, and resources under different conditions while capturing the driving force of each stakeholder in negotiating payment arrangements. Each stakeholder would be represented by an agent with specific and unique characteristics in the agent-based simulation model and by a player with specific strategies, payoffs, and goals in the game theory-based joint decision-making process.

Studying each stakeholder on an individual level would account for parameters such as their roles in the project, allocated work items, time and cost aspects, resource availability and usage, financial strength, reactions to cash flow problems, interest rates, remedies and damages, payment timing and delay patterns, in addition to interactions with other stakeholders. This would support the empowerment of stakeholders along the payment chain to actively participate in the contract negotiation process.

### 4. Methodology: Payment Management and Decision Support Framework

The proposed framework comprises the three following modules: (a) data acquisition; (b) simulation, analysis, and negotiation; and (c) decision support as illustrated in Figure 1. The first module represents the input source data which capture the specifics of the project under study. The second module focuses on the simulation, negotiation, and analysis of payment arrangements and finances by integrating agent-based modeling and simulation (ABMS) [36], data envelopment analysis (DEA) [37], and game theory [38]. The ABMS component enables modeling construction projects and involved stakeholders under various payment policies and conditions. The DEA analysis component is then used for the calculation of stakeholders' payoffs and efficiency levels under the tested strategies. Additionally, the game theory component is utilized in modeling payment negotiations among stakeholders for a symmetric and balanced payment decision. The third module finally sets the basis for decision-making and support by utilizing the outputs of Module B in adjusting payment arrangements and providing recommendations for improved performance. Further details of the framework modules are presented in the following sub-sections.



Figure 1. Proposed decision support framework for payment management and negotiation.

# 4.1. Module A: Data Acquisition

The first module of the framework is the data acquisition module which represents the source of input data for various aspects of the construction payment system including project details, schedule and cost data, progress data and performance levels, payment arrangements and legislation, contract details, and financial aspects of stakeholders. The input data may vary based on the project phase and may differ in terms of type, availability, sources, collection method, and usage.

The minimum data requirements for the effective implementation of the proposed framework is typically available in the main contract and/or subcontracts of a project. This includes data regarding work items as their precedence relationships, duration, and cost aspects, as well as responsible parties. For stakeholders, they can specify payment timings, contract values, retention, delay damages, and compensation for the owner-contractor and contractor-subcontractor links without details of their cost information and profit margins. Additional details can be included by the target user including interest rates and financing costs. Such parameters can also be assigned different values for analysis, testing, and decision-making purposes. In addition to the planned data, updating the input data is essential throughout project stages to continuously detect performance deviations or changing conditions and adjust cash flow and payment decisions while analyzing their impacts on the project and stakeholders. This process facilitates the close monitoring and control of projects which support the proposed adaptive decision-making system. Nevertheless, in data deficient environments, general industry averages and metrics can be used in developing the needed distributions for the input data to be updated upon the availability of project-specific data.

Various categories of data sources and types include documents and communications before and during project execution, as-planned BIM model for tracking work progress, and site progress data collected using various reality capture techniques. In addition to manual data acquisition, there is an abundance of technologies available for providing real-time, accurate, and reliable information of the construction process [39]. Selecting the suitable technologies depends on the studied project and required data. Finally, the quality of data gathered in this module improves the performance of Modules B and C of the framework, as explained in the following sub-sections.

#### 4.2. Module B: Simulation, Analysis, and Negotiation

The second module of the framework is the simulation, analysis, and negotiation module as detailed in the below sub-sections.

### 4.2.1. Sub-Module B.1: Payment Simulation

The payment simulation sub-module addresses the modeling and simulation of the project with a focus on the cash flow process, payment arrangements, and interactions among stakeholders throughout project execution using the data obtained in Module A. In this sub-module, discrete-event simulation (DES) and agent-based modeling and simulation (ABMS) techniques are integrated to model the progress of work items and stakeholders, respectively. Another common modeling approach is system dynamics which better describes the project cash flow system as a whole without addressing the specific characteristics of activities and stakeholders [30].

DES is a simulation technique that represents a system through a sequence of processes with events such that the state of resources related to these processes changes in discrete steps [40]. These characteristics make DES an ideal simulation technique for studying construction operations and activities as they typically follow the sequence set in a project schedule and utilize a unique combination of resources [40]. On the other hand, ABMS is a simulation modeling technique that represents a system from the perspective of its constituent units or agents that interact in and with an environment based on specified rules with the aim of predicting the potential emergent behavior [36]. Moreover, ABMS follows a bottom-up approach in setting the properties and interactive features of agents at a micro level to produce the emergent system outcome at the macro level [36].

The proposed simulation model divides the project into primary and secondary agents. The primary agents represent the project work items and key stakeholders in the payment process. As for the secondary agents, they are used to model the documentation requirements for the payment process. The description of the primary and secondary agents is detailed below.

- Work Item: models the population of project activities to model their planned and simulated schedule and cost attributes, precedence relationships, responsible stakeholders, work progress, as well as resource requirements, usage, and suppliers (if needed).
- Owner: is regarded as the investor of the project at the top of the payment chain who makes payments to the contractor agent for the work performed based on the contractual conditions.
- Contractor: refers to the main contractor who is responsible for executing and managing the construction operations of a project in return for payments from the owner agent. This agent can partially or fully subcontract work items to subcontractor agents.
- Subcontractor: models the population of subcontractors each performing one or more work items in return for monetary amounts from the contractor agent. A project may have one or more subcontractors with varying specialties and financial capacities.
- Payment Application (PayApp): represents the population of payment requests that the contractor agent periodically submits to the owner agent to receive payments for performed work. Each PayApp agent has attributes for the submission and due dates, work items included, amounts required, payment or nonpayment decision, etc.
- Invoice: represents the population of payment requests that each subcontractor agent prepares and submits to the contractor agent. In each payment period, the contractor uses such invoices in preparing payment applications that are then submitted to the owner agent to receive payments for performed work.

The stakeholders under the primary agent types have attributes for the representation of the payment process including the payment timing and pattern, interest rates, advance payments, maximum overdraft, interest charges and penalties, profit, amounts paid and received, retention, etc. Such information reflect the financial profile of the stakeholders and bottlenecks in the payment process, if any. As for the secondary agents, each has attributes for the submission and due dates, work items included, amounts required, delay interest charges, etc. This facilitates making payment decisions on an application-by-application basis rather than adopting fixed decisions for all. In this research, AnyLogic software version 8.8.5 is used for modeling and simulation. It is a general-purpose software tool that is fully mapped into Java code with libraries that support different simulation modeling methods including DES and ABMS. The database tables are developed using MS Excel and linked to AnyLogic for importing and exporting the simulation input and output data, respectively. The simulation model allows the incorporation of site data and payment details throughout the project stages to continuously adjust the payment policies based on the changing project conditions and financial performance of stakeholders. The model also accounts for uncertainties that can affect the schedule and/or costs of work items and the project. This is achieved through a stochastic simulation process by modeling the time and cost aspects of work items using probability distributions and performing a Monte Carlo simulation process with the required number of runs. Monte Carlo simulation uses random sampling of the model's stochastic input parameters to simulate a model representing a real system and provides a large number of random samples of the model output. The simulated scenarios would then be assessed as explained in Sub-module B.2.

# 4.2.2. Sub-Module B.2: Performance Analysis

The performance analysis sub-module aims to analyze the outputs of the simulation process of the tested scenarios based on their impacts on the performance of the project and stakeholders using specified performance metrics. The aim is to evaluate and relatively assess how the outputs of the tested scenarios differ based on the changed inputs. For this purpose, this sub-module utilizes the data envelopment analysis (DEA) technique for performance analysis and evaluation.

DEA is a data-oriented and non-parametric programming method introduced in 1978 for the comparative evaluation of the efficiency of a set of entities or decision-making units (DMUs) which consume multiple inputs to produce multiple outputs [37]. The efficiency of a DMU is the ratio of the weighted sum of the outputs to the weighted sum of inputs as given in Equation (1). Accordingly, the principle of efficiency is to attain the best outcome through the minimum utilization of input resources. Generally, the aim of DEA is to measure the relative efficiency of DMUs in addition to identifying whether each of the studied DMU is efficient or not, determine the degree of its efficiency, and assess where inefficiencies may arise. The DMUs can represent entities of various natures which supported the wide application of DEA [41].

$$Efficiency = \frac{Weighted \ sum \ of \ outputs}{Weighted \ sum \ of \ inputs} \tag{1}$$

The implementation of DEA in this sub-module is based on the CCR (Charnes, Cooper, and Rhodes) model proposed by Charnes et al. [37]. In this model, the efficiency of any DMU is obtained as the maximum of a ratio of weighted outputs to weighted inputs subject to the condition that the similar ratios of every DMU be less than or equal to unity. In case of n DMUs, each has m inputs  $x_i$  with unknown input weights  $v_i$  and s outputs  $y_r$  with unknown output weights  $u_r$ . Solving this model results in optimal weights for the input and output parameters that maximize the performance ratio of each DMU with a maximum value of 1. This prevents the subjectivity in setting weights based on preferences and enables forming an efficiency frontier for the DMUs under study. The relative efficiency score of a test DMU j is obtained by solving the fractional programming model (*FP*<sub>0</sub>) of DMU o where o ranges over 1, 2, ..., n as detailed in Equations (2)–(4):

$$FP_{o} \quad \max E_{o} = \frac{\sum_{r=1}^{s} u_{r} y_{ro}}{\sum_{i=1}^{m} v_{i} x_{io}}$$
(2)

subject to 
$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1$$
;  $j = 1, ..., n$  (3)

$$u_i, v_r \ge 0; \quad r = 1, \dots, s, \quad i = 1, \dots, m$$
 (4)

The fractional equation is reduced to a linear programming form  $(LP_o)$  as given in Equations (5)–(8):

$$LP_o \quad \max E_o = \sum_{r=1}^{s} u_r y_{ro} \tag{5}$$

subject to 
$$\sum_{i=1}^{m} v_i x_{io} = 1$$
(6)

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0; \quad j = 1, ..., n$$
<sup>(7)</sup>

$$u_i, v_r \ge 0; \quad r = 1, \dots, s, \quad i = 1, \dots, m$$
 (8)

DEA is incorporated in the proposed framework for the efficiency assessment of each of the primary agents or stakeholders under the studied scenarios of payment and financing policies. The DMUs in this case refer to the scenarios each having their own performance efficiency ratio. As for the inputs and outputs, they reflect different aspects of the financial performance of stakeholders as well as schedule dimensions. As such, the metrics used for the input parameters include the negative area of the cash balance curve and time extension of payments. As for those used for the output parameters, they include the positive area of cash balance curve, as well as time and cost performance metrics. The time and cost performance metrics refer to the degree of delays and charges relative to the baseline duration and contract values, respectively. Moreover, the net present value (NPV) of the cash flow is incorporated as an input parameter for the owner and an output parameter for the contractor and subcontractors. Additional parameters can be included to reflect other dimensions of the stakeholders' performance as deemed necessary. The model for this sub-module was developed using Python programming. Finally, upon the implementation of DEA on the simulation outputs, the efficiency values of stakeholders can then be used in the payment negotiation process detailed in Sub-module B.3.

#### 4.2.3. Sub-Module B.3: Payment Negotiation

The third component of Module B focuses on the negotiation of the simulated and analyzed strategies. Stakeholders of a construction project continuously interact throughout the project phases. Although stakeholders may make individual decisions following ad hoc approaches, the possible consequences of such decisions affect the involved stakeholders and the project. Accordingly, the negotiation and joint decision-making process of this component is formulated using game theory. An alternative approach to game theory for decision-making is multi-objective optimization [42]. However, the grouping of stakeholders' objectives under such approach would not respect the individualized performance of the stakeholders as required. Instead, the aim is to enable each stakeholder to focus on maximizing their individual outcomes under the strategies offered by the other stakeholders involved.

Game theory provides a unified approach by constructing mathematical models to formalize strategic situations in which a number of decision-making entities, known as players, interact to choose a strategy based on their independent and rational decision-making abilities such that the decision of each entity impacts the outcomes of the others involved [38]. Rationality is an underlying assumption in game theory which considers players to be aware of alternative strategies and select the ones that maximize their payoffs [38]. Analyzing and solving games support the understanding of the interactions between players to predict their outcomes while accounting for their individual behaviors and goals. There are numerous applications for game theory in the construction industry as reviewed by Eissa et al. [43].

The main components of a game model are the players of the strategic problem, the players' strategies and received payoffs, as well as game-specific rules for players [38]. A game-frame in strategic form is a list of four items  $\langle I, (S_1, S_2, ..., S_n), O, f \rangle$  where:

- $I = 1, 2, \dots, n$  is a set of players  $(n \ge 2)$ .
- (S<sub>1</sub>, S<sub>2</sub>,..., S<sub>n</sub>) is a list of sets, one for each player. For every Player *i* ∈ *I*, S<sub>i</sub> is the set of strategies of Player i. The set of strategy profiles S is denoted by the Cartesian product of these sets: S = S<sub>1</sub>S<sub>2</sub>...S<sub>n</sub>; thus, an element of S is a list s = (s<sub>1</sub>, s<sub>2</sub>,...,s<sub>n</sub>) consisting of one strategy for each player. A strategy profile s without player *i*'s strategy is formally denoted as s<sub>-i</sub> such that s<sub>-i</sub> = (s<sub>1</sub>,...,s<sub>i-1</sub>,s<sub>i+1</sub>,...,s<sub>n</sub>). Thus, a strategy profile s can be written as s = (s<sub>i</sub>, s<sub>-i</sub>).
- O is a set of outcomes of the players with π<sub>i</sub> representing the payoffs received by player i.
- *f* : *S* → *O* is a function that associates with every strategy profile s an outcome *f*(*s*) ∈ *O*.

Two game formulations are proposed for studying the payment negotiation process with the payoffs set based on the DEA results as explained hereafter.

The first game formulation is a two-step two-player game structure of two interacting games referred to as Game OC and Game CS. Figure 2 illustrates the interactions within and between the two games. Game OC focuses on the link between the owner and the contractor such that the owner undergoes a negotiation process with the contractor to set the requirements for payment policies, including the advance payment, payment frequency and timing, interest charges, and payment application submission basis. Game CS focuses on the link between the contractor and subcontractor(s) to negotiate similar strategies that shape their payment interactions. In case of more than one subcontractor, they can be grouped as one entity with relative weights to simplify the game analysis. Such weights may be determined by their respective contribution to the project cost, criticality of work items, financial capacities, or given equal priorities. Following this structure, each game can be studied separately to identify the solution strategies for its stakeholders, then the common solution strategies of all involved stakeholders in both games would be selected.



Figure 2. Two-step two-player game model for Games OC and CS.

The second game formulation is based on the interaction among the three primary stakeholder groups in a three-player game referred to as Game OCS as presented in Figure 3. The figure reflects the joint incorporation of the performance of all stakeholders for setting the payment policies to reach a compromise and an acceptable level of risk transfer. Similar to the two-player game structure, the subcontractors are also grouped as one entity with relative weights. It is worth noting that although there is no direct contractual relation between the owner and subcontractor(s), the payment policies and performance of each stakeholder will indirectly impact the other. Therefore, the game does not entail having

a contractual relation, but an impact and effect represented through the game payoffs. This mutual interaction of stakeholders is already incorporated in the simulation process. In this regard, this option allows the active participation of the three players in the decision-making process.



Figure 3. Three-player game model for Game OCS.

The two and three-player games were represented in a normal or matrix form. There are various approaches that can be adopted for analyzing and solving games. However, one of the most common analysis approaches used in non-cooperative games is the Nash equilibrium. A Nash equilibrium is a strategy profile *s* with a combination of strategies in which no single player can obtain a higher payoff by unilaterally changing their strategy [38]. If  $\pi_i$  represents the payoffs received by player *i*, then the Nash equilibrium of the game can be formally given as shown in Equation (9):

$$\forall_{i}, \, \pi_{i}(s_{i}^{*}, s_{-i}^{*}) \geq \pi_{i}(s_{i}^{'}, s_{-i}^{*}), \quad \forall s_{i}^{'}$$
(9)

A Python code was developed to formulate the payoff matrices of the two and threeplayer games using the performance efficiency obtained in the DEA model. The code facilitates the automated game formulation and solution process based on the Nash equilibrium. This was followed by the identification of the pure Nash equilibria for the studied games using Pygambit library in Python. The game models can provide a useful reference point for payment analysis to capture the driving force of stakeholders and assess their perspectives on the payment process.

# 4.3. Module C: Decision Support

The third module of the framework is the decision support module which focuses on making payment decisions that enhance project performance and satisfy the individual and collective requirements of stakeholders. This module extends the results of the integration and inter-relationships between the data acquisition in Module A with the simulation, analysis, and negotiation in Sub-modules B.1, B.2, and B.3, respectively, to maintain balanced payment interactions. As shown in Figure 4, the framework considers the agents in the simulation process as the players in the game theory models. The figure also shows the behaviors, states, and parameters of each agent, as well as the interactions with other agents. Accordingly, the various performance assessment indicators developed in Sub-module B.2 reflect the effects of the varying payment conditions together with the different degrees of stakeholders' influence or authority levels set in Sub-module B.3. Therefore, this module will facilitate making adjustments to the payment arrangements and provide recommendations for improved performance of the project and stakeholders.



Figure 4. Integration of Modules A and B in the framework for the decision support in Module C.

The framework can be used by various target users to capture the different perspectives of the payment process based on the agents incorporated in each case as follows: (i) Owner: owner- contractor-work items; (ii) Contractor: owner-contractor-subcontractor(s)-work items; (iii) Subcontractor: contractor-subcontractor-subcontractor's work items; and (iv) Governmental/legislative bodies and research entities: same as contractor. The model level of detail will be based on the target user and available data. This will be reflected by the selected agents and work items which can represent specific activities, work packages, or milestones. For instance, the owner and subcontractors can use the framework for the simulation and analysis to analyze potential strategies and expected outcomes. As for the contractor, governmental/legislative bodies, and research entities, they can benefit from the simulation, analysis, and negotiation processes required for decision-making. The contractor will have three game scenarios as contractor-owner, contractor-subcontractors, and owner-contractor- subcontractors.

Potential applications of the framework include the analysis of the financial performance of projects and stakeholders under varying contractual provisions, payment practices, schedule delays, cost overruns, external factors, supply chain disruptions, construction options, and other factors that affect their performance. The analysis results obtained can then be utilized in setting and adjusting the payment provisions of contracts and subcontracts regarding payment timing, delay remedies, productivity changes, interest rate fluctuations, compensation, etc. Furthermore, the framework can support collaborative contractual environments including integrated project delivery (IPD) projects where all stakeholders are actively participating in a joint decision-making process. The framework can also be used as an objective platform to support stakeholders in quantifying their payment and compensation requirements during dispute resolution.

The proposed framework is designed to incorporate and manipulate the various parameters of the cash flow and payment system of projects and stakeholders. The usage of agent-based modeling facilitates the customization of the developed model with its constituent agents of the work items and stakeholders along with their interactions. This enables addressing cash flow issues under different project categories, markets of specific geographic features, delivery methods, prompt payment acts, and economic conditions.

#### 5. Framework Implementation

This section presents the implementation of the proposed framework in a case study project showing the implementation of its modules along with the obtained results. The implementation steps are demonstrated in the flowchart in Figure 5 and are based on integrating the three modules of the framework for data acquisition, payment simulation, analysis, and negotiation, as well as the decision support.

An MS Excel-based system was developed for the data acquisition module of the framework to capture the input data of the project under study regarding the work items and financial details of stakeholders. However, other linked database tables can be used as well. The data requirements for the schedule and cost details should be available for the planning of any construction project and are imported from the schedule developed in Primavera P6 or other similar project management software. As for the financial details, the input data is set according to the required payment scenarios and are captured using a Python GUI that was developed for populating the database. The MS Excel-based system is then linked to AnyLogic for a dynamic simulation process.

The payment scenarios were simulated and tested using the integrated discrete event and agent-based model developed in AnyLogic with the primary and secondary agents. After the simulation, the outputs were then used as the basis for the performance analysis of stakeholders using the Python-based DEA model developed for the framework. The resulting efficiency values obtained represent the payoffs of the stakeholders under the tested scenarios. The DEA efficiency values were then incorporated in the payment negotiation process of the various payment strategies through game theory based on two and threeplayer game structures using the Python-based code that was developed for formulating the required matrix structures. In the game formulation and analysis, the subcontractors were grouped as a single entity with equal weights which could be adjusted as needed. Based on the obtained results, the decision support process followed to identify suitable and balanced payment policies for the involved stakeholders.



Figure 5. Implementation flowchart of the framework.

## 5.1. Case Study Description and Scenario Design

The case study project used for the framework implementation is a multi-purpose commercial and administration building at a central business project (CBP) located in west Cairo, Egypt. The CBP is comprised of nine buildings over an area of 35,000 m<sup>2</sup>, with each building having two basement levels for car parking, lower ground floor and ground floor for retail purposes, and six repetitive floors designed to provide a combination of activities including service businesses, administrative offices, and medical facilities. The building under study (B4) has a footprint area of 1020 m<sup>2</sup> with a total built-up area of 8529 m<sup>2</sup>, and is executed as core and shell.

The case study project of building B4 is composed of 238 work items that are divided into seven billing elements which are Mobilization, Foundation, Concrete Works, Masonry, Internal Finishes, Mechanical, Electrical, and Plumbing (MEP), as well as External Finishes. The contractor is assumed to subcontract work items under the Internal and External Finishes as well as MEP, representing almost 67% of the project, each performed by a separate subcontractor. The project follows a design-bid-build delivery method and is performed on a lump sum contract basis. The details of the work items are presented in Supplementary Table S1, including their respective subcontractor category, duration, direct costs, indirect costs, and precedence requirements. The profit is set to be 10% for the contractor and subcontractors whereas the contractor's overhead represent 10% of the total direct costs, resulting in a contract value of USD 53,261,612 with a duration of 315 days.

The project is studied under two analysis categories to offer a comprehensive assessment of the financial performance of the owner, contractor, and subcontractors as detailed below.

- Analysis 1: normal work productivity with different payment cycles and status which include timely payment conditions, delayed payment conditions, and mixed payment conditions of delayed payment to the contractor and timely payment to the subcontractors.
- Analysis 2: changing work productivity under delayed payment conditions from normal productivity to reduced productivity by 10% and 20%.

Each of these analysis conditions is studied under changing parameters of payment cycle, payment status, interest rate, and advance payment. The values assigned for these parameters are only selected for demonstrating the efficacy of the proposed framework, but other conditions can also be considered. A coding system is followed to define the details of the scenarios for the owner, contractor, and subcontractors as shown in Equation (10):

$$O(i_1, i_2) - C(j|k_1, k_2, k_3) - s(l, m, n)$$
(10)

such that,

- O: Owner
  - $i_1$ : PayApp payment timing as 1 = 28, 2 = 60, or 3 = 90 days.
  - $i_2$ : PayApp payment status as 1 = Timely, or 2 = Delayed.
- C: Contractor (Con-Own|Con-Subs)
  - j: Advance payment percentage from Owner as 1 = 0%, 2 = 5%, or 3 = 10%.
  - $k_1$ : Invoice payment timing as 1 = 35, 2 = 60, or 3 = 90 days.
  - $k_2$ : Invoice payment status as 1 = Timely, or 2 = Delayed.
  - $k_3$ : Work productivity as 1 = Normal, 2 = Reduced 10%, or 3 = Reduced 20%.
- s: Subcontractors
  - l, m, n: Advance cash percentage for high, medium, and low priority subcontractors as 1 = 0%, 2 = 5%, or 3 = 10%. They are assumed to have equal values.

The base case scenario of the case study follows prompt payment conditions to contractors and subcontractors of 28 and 35 days, respectively [8]. These values are used as a reference for payment delays. Other assumptions for the simulation process are as follows:

• The annual interest charge rate *I* is assumed to be 6%, 8%, 10%, 12%, 14%, and 16%.

- The net present value (NPV) for stakeholders is calculated at the same interest rate *I*.
- The stakeholder delaying payment for PayApps or Invoices would pay interest charges at a rate (I + 0.25)% as a delay penalty and compensation to the affected stakeholder.
- The stakeholder with an overdraft incurs finance interest charges at a rate (I + 1.0)%. This amount varies based on the stakeholder's financial capacity and risk profile.
- A retention of 10% is deducted from each payment and released after the project completion.
- A reduction in the productivity rate equivalently reduces subcontractor's indirect cost.
- The project operates on a schedule of 6 working days per calendar week with an 8-h working shift per day.

The studied scenarios are also designed to account for uncertainties and randomness during project execution through a stochastic simulation process performed based on Monte Carlo simulation. This is achieved by providing probabilistic distributions for the input metrics such as duration and cost distributions for work items. A triangular distribution is assumed for both the duration and cost aspects with a variation of  $\pm 10\%$ from the values set in Supplementary Table S1. However, other distributions can be used as well based on project-specific data, historical data, literature, best practices, or surveys.

## 5.2. Implementation of Analysis 1 Scenarios

This sub-section presents the highlights of Analysis 1 scenarios which are based on normal productivity and different payment cycles. The DEA model was implemented and the efficiency values are presented in Figure 6a for the owner versus the contractor and Figure 6b for the contractor versus the grouped subcontractors. This classification follows the structures of Game OC and Game CS, respectively. The figure is organized with the payment cycle and status specified by the columns, the advance payment percentage set for each row, and the interest rate shown on the studied scenarios. The DEA values displayed are under interest rates ranging from 6% to 16% for Payments 1, 2, and 3. An inclined line is also included to represent the equality points for each of the two stakeholders. As for the advance payment, the values presented are for 0% and 10% to represent the extreme cases with the other value in between. The following can be observed from the figure:

- For the owner: Under timely payment, the owner's DEA values increase with the elongation of the payment cycle with the highest levels under Payment 3. Under delayed payment, the DEA values are relatively lower than those under the timely conditions with a slight decrease for Payment 3 compared to that of Payment 2. This stems from the owner's responsibility to pay the interest charges of delayed payment to the contractor which further increase with the payment delay (Payments 2 and 3). Under all payment conditions, the DEA values decrease with the increase in the interest rate for their effect on the NPV of the payments made. Similarly, the DEA values decrease with the increase in the advance payment percentage since more amounts are made at the project initiation which counters the benefits of the elongated payment cycles.
- For the contractor: Under timely payment, the DEA values decrease with the elongation of the payment cycle with Payment 1 providing the highest efficiency levels. Under mixed and delayed payment, the DEA values are relatively higher than the timely conditions of their respective elongated cycles since additional delay interest charges would be received from the owner. However, delaying payment to subcontractors shows slight improvement in the DEA values compared to the mixed payment conditions which entail the prompt payment to subcontractors yet is limited by the additional delay interest charges that are to be made. Under all payment conditions, the DEA values increase with the increase in the advance payment percentage as it improves the contractor's financial profile throughout the project.
- For the subcontractors: Under timely payment, the DEA values decrease with the elongation of the payment cycle (Payments 2 and 3) as a result of the reduced NPV and increased financing charges. Under delayed payment, the DEA values show slight increase relative to their respective payment cycles under timely payment as a result of the additional interest charges received from the contractor which improves their



financial performance. Under all payment conditions, the DEA values increase with the increase in the advance payment percentage.

**Figure 6.** DEA payoffs of Analysis 1 for case study project. (**a**) Game OC for owner and contractor. (**b**) Game CS for contractor and grouped subcontractors.

The DEA results are then used as the payoffs of the stakeholders or players in the two and three-player games. The solution strategies were obtained based on Nash equilibrium and are provided in Table 1. The solutions are categorized according to the studied payment cycles but are mostly under Payment 1 with the different advance payment percentages. Among these strategies, the owner's efficiency is negatively affected by the increase in the advance payment as opposed to the contractor and subcontractors. Under Payments 2 and 3, the solutions are under timely payment with no advance payment. Under such conditions, the owner's efficiency levels are improved relative to Payment 1 as opposed to that of the contractor and subcontractors. Furthermore, the solution strategies are generally repeated under the studied interest rates which can be considered as being invariant to the interest rate fluctuations, within the studied limits. Accordingly, selecting among such strategies would enhance the performance stability under changing economic conditions.

Table 1. Game theory solutions for payment strategies of Analysis 1 for case study project.

Interest Rate	Payment 1 (28 Days)	Payment 2 (60 Days)	Payment 3 (90 Days)		
6%	O(1,1)-C(1 1,1,1)-s(1,1,1): (0.9952, 0.9909, 0.9963) O(1,1)-C(2 1,1,1)-s(2,2,2): (0.9881, 0.9958, 0.9978) O(1,1)-C(3 1,1,1)-s(3,3,3): (0.9862, 1.0000, 1.0000) *	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9992, 0.9166, 0.9226)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8644, 0.8665)		
8%	O(1,1)-C(1 1,1,1)-s(1,1,1): (0.9927, 0.9879, 0.9966) O(1,1)-C(2 1,1,1)-s(2,2,2): (0.9842, 0.9940, 1.0000) O(1,1)-C(3 1,1,1)-s(3,3,3): (0.9816, 1.0000, 0.9995) *	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9965, 0.9108, 0.9251)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8535, 0.8538) O(3,1)-C(2 3,1,1)-s(2,2,2): (0.9967, 0.8656, 0.8680)		
10%	O(1,1)-C(1 1,1,1)-s(1,1,1): (0.9921, 0.9832, 0.9966) O(1,1)-C(2 1,1,1)-s(2,2,2): (0.9800, 0.9952, 0.9963) O(1,1)-C(3 1,1,1)-s(3,3,3): (0.9771, 1.0000, 1.0000) *	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9967, 0.9009, 0.9287)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8419, 0.8466)		
12%	$\begin{array}{l} O(1,1)\text{-}C(1 1,1,1)\text{-}s(1,1,1)\text{:} (0.9899, 0.9811, 0.9954)\\ O(1,1)\text{-}C(2 1,1,1)\text{-}s(2,2,2)\text{:} (0.9762, 0.9929, 0.9988)\\ O(1,1)\text{-}C(3 1,1,1)\text{-}s(3,3,3)\text{:} (0.9724, 1.0000, 1.0000) \ ^* \end{array}$	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9971, 0.8943, 0.9125)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8303, 0.8375)		
14%	$\begin{array}{l} O(1,1)\text{-}C(1 1,1,1)\text{-}s(1,1,1)\text{:} (0.9870, 0.9766, 0.9940)\\ O(1,1)\text{-}C(2 1,1,1)\text{-}s(2,2,2)\text{:} (0.9721, 0.9915, 0.9945)\\ O(1,1)\text{-}C(3 1,1,1)\text{-}s(3,3,3)\text{:} (0.9678, 1.0000, 0.9990) * \end{array}$	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9948, 0.8847, 0.9183)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8144, 0.8200)		
16%	$\begin{array}{l} O(1,1)\text{-}C(1 1,1,1)\text{-}s(1,1,1)\text{:} (0.9874, 0.9702, 0.9927)\\ O(1,1)\text{-}C(2 1,1,1)\text{-}s(2,2,2)\text{:} (0.9685, 0.9888, 0.9924)\\ O(1,1)\text{-}C(3 1,1,1)\text{-}s(3,3,3)\text{:} (0.9634, 1.0000, 0.9971) * \end{array}$	O(2,1)-C(1 2,1,1)-s(1,1,1): (0.9935, 0.8767, 0.9224)	O(3,1)-C(1 3,1,1)-s(1,1,1): (1.0000, 0.8006, 0.8179)		

\* The solution strategy that is common in the two and three-player games.

# 5.3. Implementation of Analysis 2 Scenarios

This sub-section presents the highlights of the Analysis 2 payment scenarios, which are based on changing work productivity. The DEA model results are summarized in Figure 7a for the owner versus the contractor and Figure 7b for the contractor versus the grouped subcontractors. The figure is organized based on the payment cycle and status, the advance payment percentage, and the interest rate. The timely payment conditions under Payment 1 are included as a reference for the studied scenarios but are not included in the game formulation and solution. As for the delayed payment conditions, each payment cycle is displayed separately under work productivity levels of normal, 10% reduction, and 20% reduction. The following can be observed from the figure:

- For the owner: Under Payments 2 and 3, the DEA values are highest for the normal work productivity and decrease with the reduction in work productivity as well as the elongation of the payment cycle. However, the DEA values decrease with the increase in the interest rate and advance payment percentage for their negative effects on the NPV.
- For the contractor: Under Payments 2 and 3, the DEA values are also highest for the normal work productivity and decrease with the reduction in work productivity and the elongation of the payment cycle. In addition, the DEA values increase with the increase in the advance payment percentage. Despite the reduction in the indirect costs based on the reduced productivity levels, the elongation of the project duration reduces the DEA values for their impact on the time performance of the work items and the project as a whole.
- For the subcontractors: Under Payments 2 and 3, the DEA values show a similar pattern as that of the owner and contractor by showing reduced levels with the reduction in work productivity. This reduction in the DEA levels is slightly improved with the increase in the advance payment percentage. This pattern in the DEA values is caused by the decrease in the NPV levels as well as the area negative of the cash flow since the delayed performance in turn delays the amounts received.



**Figure 7.** DEA payoffs of Analysis 2 for case study project. (**a**) Game OC for owner and contractor. (**b**) Game CS for contractor and grouped subcontractors.

The DEA values are then used as the payoffs in the game theory sub-module. The solution strategies of the two and three-player games are provided in Table 2 under changing interest rates. The solutions obtained are mostly under Payment 2 with normal work productivity and varying advance payment. The solution strategies also reflect the conflicting performance levels for the owner as well as the contractor and subcontractors with the variation of the advance payment. It can also be observed from the table that the solution strategies are generally repeated under the studied interest rates, which can be considered as being invariant to the change of interest rate, within the studied limits.

Interest Rate	Normal Work Productivity
6%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9958, 0.9251, 0.9383) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9930, 0.9311, 0.9271) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9917, 0.9373, 0.9347) * O(3,2)-C(1 3,2,1)-s(1,1,1): (0.9960, 0.8767, 0.8814)
8%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9948, 0.9211, 0.9338) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9931, 0.9281, 0.9372) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9906, 0.9375, 0.9414) *
10%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9957, 0.9164, 0.9330) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9924, 0.9264, 0.9403) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9900, 0.9369, 0.9379) *
12%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9951, 0.9102, 0.9322) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9914, 0.9245, 0.9362) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9883, 0.9351, 0.9487) *
14%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9949, 0.9061, 0.9273) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9899, 0.9217, 0.9321) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9858, 0.9353, 0.9315) *
16%	O(2,2)-C(1 2,2,1)-s(1,1,1): (0.9947, 0.8984, 0.9349) O(2,2)-C(2 2,2,1)-s(2,2,2): (0.9896, 0.9198, 0.9415) O(2,2)-C(3 2,2,1)-s(3,3,3): (0.9844, 0.9343, 0.9413) *

Table 2. Game theory solutions for payment strategies of Analysis 2 for the case study project.

\* The solution strategy that is common in the two and three-player games.

## 5.4. Implementation Highlights

A sample of the case study payment scenarios was selected to further demonstrate the impacts of these conditions on some performance aspects of the stakeholders including delay interest charges, financing costs, as well as profit changes. Table 3 provides the interest charges received and incurred by the contractor relative to the main contract value. The table shows three categories of interest charges that were included in the model, which are the financing interest charges paid by the contractor, the delay interest charges received from the owner, and the delay interest charges paid to the subcontractors. The payment links of the owner–contractor and contractor–subcontractors are presented in the table under the 60 and 90 days payment cycles, timely or delayed conditions, advance payment of 0% or 10%, interest rate of 6% and 16%, with or without retention deduction, and under normal or reduced work productivity. Among the presented payment conditions, timely payment conditions (T) refer to scenarios with no compensation being made whether the contract stipulates prompt or elongated payment cycles (Payments 2 and 3). As for delayed payment conditions (D), they would entail providing compensation for delaying payments relative to the prompt payment conditions.

The analysis of payment arrangements showed that for the cases of elongated payment cycles of 60 and 90 days, the contractor and subcontractors should be fairly compensated to avoid the increased financing charges incurred that could reach 2.8% and 4.7% of the main contract and subcontracts, respectively. These charges would further increase with the increase in the interest rate and cause additional financial distress. Based on the case study assumptions, the owner and contractor may incur interest charges up to 2.8% and 1.4% of the contract value to compensate the delayed payments to the contractor and subcontractors, respectively. As such, the ideal and balanced solution conditions among the studied scenarios would be those following the shortest payment cycle.

It follows from the interest charges provided that the contractor's profit would be affected under timely and delayed payment conditions as illustrated in Figure 8. The figure shows that the decrease in the contractor's profit can reach 7% and 19% under Payments 2 and 3, respectively, in case of an interest rate of 16% with no compensation received

from the owner along with the early payment to the subcontractors. A similar analysis was performed for the subcontractors and the profit was reduced by 14% and 35% under elongated cycles of Payments 2 and 3, respectively, with no compensation. However, the inclusion of advance payments showed a noticeable improvement in the profit reduction. Moreover, the variation of the interest rate also resulted in variations in the interest charges as well as the profit, which reflects the criticality of accounting for the interest rate in the contract negotiation process. Nevertheless, the implementation of the game theory sub-module resulted in solutions that are invariant to the fluctuations of the interest rates under the studied ranges.

Interest Charges	Advance Payment %	Payment Condition (OwnCon–ConSubs)	Payment 2: 60 Days (Int Rate 6–16%)	Payment 3: 90 Days (Int Rate 6–16%)
Financing	0%	(1) Timely–Timely	0.39-1.00%	0.59-1.50%
Charges		(2) Delayed–Timely (Payment 1: 35 days)	0.58-1.44%	1.06-2.60%
Paid		(3) Delayed–Delayed	0.39-0.97%	0.58-1.46%
		(4) Timely–Timely (Payment 1: 35 days)	0.57-1.46%	1.06-2.76%
		(5) Timely (no retention)–Timely (no retention)	0.31-0.80%	0.51-1.28%
		(6) Delayed–Delayed (Productivity reduction 20%)	0.40-1.00%	0.60-1.49%
	10%	(1) Timely–Timely	0.06-0.14%	0.22-0.53%
		(2) Delayed–Timely (Payment 1: 35 days)	0.21-0.51%	0.62-1.49%
		(3) Delayed–Delayed	0.05-0.13%	0.21-0.50%
		(4) Timely–Timely (Payment 1: 35 days)	0.21-0.52%	0.61-1.56%
		(5) Timely (no retention)–Timely (no retention)	0.02-0.06%	0.14-0.36%
		(6) Delayed–Delayed (Productivity reduction 20%)	0.04-0.09%	0.18-0.42%
Delay Charges	0%	(2, 3, 6) Delayed–Timely (Payment 1)/Delayed	0.55-1.43%	1.06-2.79%
Received	10%	(2, 3, 6) Delayed–Timely (Payment 1)/Delayed	0.49–1.28%	0.96–2.51%
Delay Charges	0%	(3) Delayed–Delayed	0.24-0.63%	0.53-1.39%
Paid	10%	(3) Delayed–Delayed	0.22-0.57%	0.48-1.25%

**Table 3.** Percentages of the contractor's interest charges relative to the contract value for case study project.

By changing key parameters in the model, each stakeholder will be able to simulate cash flow conditions under different payment and financing scenarios, and therefore evaluate the costs and benefits of specific contract clauses in terms of their impact on project cash flows. The proposed framework was implemented under changing conditions of payment cycle and status, interest rate, advance payment, and work productivity to elaborate its flexibility and efficacy.

The payment cycle and status are typically controlled by upper-tier stakeholders who show higher performance levels when following elongated payment cycles. This explains the industry-wide practice of late payments and unfair provisions. Nevertheless, the obligation of paying interest charges for delayed payment as dictated in various prompt payment legislation would reduce the potential benefits that stakeholders may gain from delaying payments.

For the interest rate, it is generally uncontrollable by stakeholders and determined according to the economic conditions, political stability, inflation, financing agencies, project characteristics, and stakeholder's financial capacity. In addition, obtaining solutions that are invariant to the studied interest rates may not necessarily be the case. This confirms the importance of the accurate consideration and estimation of interest rate in the financial planning and management of projects.

As for the advance payment, it has been observed from the results of Analyses 1 and 2 that the advance payment has a positive impact on the cash flow of the contractor and subcontractors. Without such amounts, contractors and subcontractors may have negative net cash flow until the final stages of the project. Despite their potential benefits, advance

payments negatively affect the owner, since more amounts would be paid at the project initiation, which in turn increases the net present values.

The final aspect is the variation of work productivity under delayed payment conditions. The contractual conditions of projects may prohibit the suspension or reduction in work productivity rates by contractors and subcontractors, yet such actions still occur in practice. The DEA and game solutions confirm the negative consequences of work suspension or reduced productivity for the involved stakeholders.







It was demonstrated from the case study that the conflicting objectives of stakeholders require careful consideration in the decision-making process. The solution strategies should offer a compromise and an acceptable level of risk transfer among stakeholders for an improved performance without unnecessary financial stresses. This would be an ongoing process to account for changing conditions and needed adjustments. In this regard, the framework effectively addresses the research gaps outlined in the Literature Review section. It provides a balanced assessment of the uncertainties attributed to cash outflows and inflows using agent-based and Monte Carlo simulations in a quantitative bottom-up approach that accounts for stakeholders along the payment chain. Moreover,

it facilitates the continuous adjustment of cash flow and payment decisions using up-todate information of the actual conditions of the project and stakeholders. Furthermore, the game theory formulation accounts for the individual roles of stakeholders and supports their active participation in a balanced decision-making process. Finally, the framework modules are designed to flexibly accommodate projects of varying complexities with limited modification requirements.

# 6. Validation of the Proposed Framework

A fundamental component incorporated during and after the implementation of the framework is the validation process performed to check the suitability of the framework and its integrated modules for studying and negotiating payment policies in construction projects. However, the nature of the developed framework limits the potential approaches that could be used for its validation since it focuses on the financial performance of stakeholders, which is not typically disclosed with the schedule and cost information of construction projects. Accordingly, the validation approach adopted is based on comparing the results of the simulation model to the results obtained using other analytic or simulation models.

The simulation model was implemented on two case studies from the literature by Elazouni and Gab-Allah [44] and Tabyang and Benjaoran [45] that used the same project of five activities along with a single owner, contractor, and subcontractor under different conditions and assumptions. This case study project was first used to introduce the finance-based scheduling (FBS) approach and demonstrate the stages of its application [44]. In this study, the project was assessed under specific owner-contractor and contractorsubcontractor payment arrangements and the schedule was studied under early and late conditions as well as constrained and unconstrained credit limits for the contractor to determine the cash flow and maximum cash requirements in such cases. The same project was then studied under varied contractor-subcontractor payment arrangements to investigate the effect of the billing date and payment time delay on the projected maximum overdrafts and financing costs [45]. The analysis demonstrated the significant impacts of subcontractor payments on the project finance and abiding by the financial constraints of the contractor. This project was effectively used for validating the simulation model by implementing it under the two conditions of payment arrangements using the proposed payment simulation model developed in AnyLogic which resulted in the same reported outputs for the cash flow, overdraft, ad financing costs. As for the performance analysis and payment negotiation sub-modules, they were verified using general examples on DEA and game theory, which also showed accurate performance.

As reflected through the framework implementation, the framework is designed to be comprehensive and flexible so as to enable adjusting payment and financing policies to analyze their impacts on projects and stakeholders. Such variability in the data requirements could not be satisfied with the execution of projects under a single strategy following the contractual conditions. Nevertheless, the assumptions, operation, and results of the framework were reviewed by experts in the field of construction project management and they provided positive feedback on the overall utility and performance of the framework.

## 7. Conclusions

This paper presented a novel adaptive and comprehensive decision support framework that integrates discrete event and agent-based modeling and simulation, data envelopment analysis, and game theory for the simulation, analysis, negotiation, and management of construction cash flow and payment arrangements during both the planning and execution stages. The framework structure facilitates a multi-level analysis of the performance of projects, stakeholders, work items, and resources under varying conditions of payment arrangements, financing policies, negotiation strategies, as well as project and external factors. This structure of the framework supports the individual representation of each stakeholder involved in the project to facilitate a quantitative bottom-up analysis of the cash flow and payment process. The implementation of the proposed framework was demonstrated through a case study project of a multi-purpose commercial and administration building under conditions of normal and reduced work productivity under changing parameters for the payment cycles, status, interest rates, and advance payment percentages. The results showed that the balanced solution conditions among the studied scenarios were those following the shortest payment cycle. As for the cases of elongated payment cycles, the contractor and subcontractors should be fairly compensated to avoid the increased financing charges incurred that could reach 2.8% and 4.7% of the main contract and subcontracts, respectively. Based on the case study assumptions, the owner and contractor may incur interest charges up to 2.8% and 1.4% of the contract value to compensate the delayed payments to the contractor and subcontractors, respectively.

It follows from the results that the profits of the contractor and subcontractors would be reduced under elongated payment cycles by a range from 7% to 19% as well as 14% and 35%, respectively, in the case of a 16% interest rate with no compensation. However, the inclusion of advance payments offer a noticeable improvement in the profit reduction. Therefore, the additional incurred charges that are often overlooked by stakeholders can greatly affect their planned profits. This is further intensified by the economic instabilities and interest rate increases which cause additional financial distress and affect sustainable construction project delivery. Accordingly, it is crucial to account for the interest rate in the contract negotiation process. Nevertheless, the implementation of the game theory sub-module resulted in solutions that are invariant to the fluctuations of the interest rates under the studied ranges.

To conclude, the framework can be used to quantify the variability of stakeholders' financial profiles under different payment provisions and legislation, finance-related conditions, and external factors. This provides each stakeholder with a detailed understanding of the cascading consequences of their payment or nonpayment decisions to avoid the adoption of imbalanced strategies that would negatively affect their individual and collective gains. As such, the framework contributes to the empowerment of stakeholders through an informed process of joint decision-making and contract negotiations. It can also be employed as an objective platform to support stakeholders during dispute resolution. In this regard, many target users can utilize this approach including the owner, contractor, subcontractor, governmental/legislative bodies, and research entities based on their requirements and perspectives on the payment process.

Future research would address the integration of the framework with other technological solutions including blockchain and smart contracts to demonstrate its support of an adaptive and continuous negotiation process throughout the lifecycle of construction projects. Moreover, the scenario design and analysis may also incorporate other aspects of construction projects including different types of construction contracts, varying risk allocation, and changing external conditions. This can include the implementation of the framework in projects with collaborative contracting settings, such as integrated project delivery. Finally, the framework could also be applied to other major and complex construction projects to illustrate its wide applicability and benefits.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16010244/s1, Table S1. Scheduling and cost details of building B4 of the CBP case study project.

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