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Optimal Design for Construction Supply Chain under Time Value of Money, Inventory Control, and Carbon Tax Consideration

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Abstract

This study develops an innovative strategy of Single Setup Multiple Delivery (SSMD) to control inventory and analyze the costs of the Construction Supply Chain (CSC) by formulating a Mixed-Integer Nonlinear Programming (MINLP) model that incorporates a Carbon Emission Scheme. Despite extensive research on CSCs, none have simultaneously addressed the integration of Net Present Value (NPV), inventory control strategies, and carbon tax policies, leaving a critical gap in optimizing cost and sustainability. Through this integrated approach, the value of money changes over time, and the NPV has been included in the calculations to analyze optimal periods with the best Rate of Return (ROR) where NPV is positive. The results of this study show that implementing the SSMD strategy leads to an increase in transportation costs while reducing holding costs. Furthermore, as the problem's complexity increased, the gap between the budget and chain costs also increased, bringing the study closer to its main goal of minimizing deviations from the budget. Additionally, as the dimensions of the problem increased, all chain costs, except for transportation, showed a constant trend. Incorporating the time value of money into the model involves considering the impact of the inflation rate on costs. The results showed that changes in the ROR led to an increase in costs. This study demonstrates that the implementation of the Carbon Tax Policy does not impact acceptable performance despite changes in the tax parameter. This study advances prior research by integrating NPV, SSMD, and carbon tax into a unified framework, demonstrating that the implementation of the Carbon Tax Policy does not impact acceptable performance despite changes in the tax parameter. The transportation costs show a consistent level of stability across various sizes of the Supply Chain (SC). Also, the longer the time horizon becomes, the smaller the NPV values, so it is more economical to complete the project in a shorter time horizon.

Keywords: Construction Supply Chain, Net Present Value, Augmented Epsilon-Constraint, Inventory Control, Single Setup Multi Delivery, Carbon Emissions.

1. Introduction

The construction industry, as one of the main pillars of economic development, plays a significant role in creating infrastructure and employment. However, the inherent complexities of this industry have made optimal SC design a major challenge. On the other hand, unfavorable SC performance can lead to a significant increase in costs, time delays, and a decrease in project quality. Hence, the development of efficient and multi-objective decision-making models for the design and optimization of the CSC is an undeniable necessity and can have a significant impact on increasing productivity and reducing the risk of construction projects. The CSC involves complex interactions that occur throughout the life cycle of a construction project. It consists of multiple stakeholders and is distinct from other industrial SCs [1]. CSC is primarily associated with bulky and heavy materials, where transportation is subject to special conditions. In contrast, a generic SC covers a wide range of products. In a generic SC, the material demand is more predictable and is usually seen in segments with specific consumption patterns. However, CSCs may experience delays and changes that lead to uncertainty. General SCs operate on a shorter timeline and focus on daily production and distribution cycles, while CSCs are project-specific and often long-term. Considering the nature of construction projects, the use of materials in large quantities and with a low unit price can be costly for managers. Therefore, effective inventory control is very important for construction managers. The discussion of costs and inventory control in CSCs is crucial. Attention should be paid to ensure that these factors do not exceed the budget of the construction project [2]. Define any sudden and unexpected increase in the project budget as a cost overrun, which should be avoided in the SC. In addition to cost control, inventory control, and budget management,

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considering the time value of money is essential. Money available now is more valuable than money in the future [3], so completing the project within a specific timeframe is crucial. This helps in compensating for the interests of the CSC in terms of cost control, budget management, and inventory. Other factors that can contribute to an optimal CSC include addressing environmental concerns, reducing carbon emissions, and selecting the right suppliers. By incorporating environmental considerations, the sustainability of the CSC is enhanced. Choosing the right suppliers can improve quality, reduce costs, and minimize delays in project completion.

Robust optimization techniques can address uncertainties in the CSC model, specifically focusing on: i) the sensitivity of backup sourcing and back-ordering decisions to associated cost factors, and ii) the effects of the SC inventory system on overall cost and risk management [4]. However, the time value of money was not taken into account. Singh et al [5] used the Fuzzy Decision Testing and Evaluation Method to determine the influencing relationships of performance indicators on the level of flexibility in CSCs. However, this method does not optimize the CSC.Jiang et al [6] presented pricing models for prefabricated CSCs using game theory. However, game theory alone cannot serve as a specific method for optimizing CSCs. Using a multi-objective mathematical model to design the CSC and optimize its operations is a significant step in the chain's design process. However, Abdolazimi et al. [7] were unable to incorporate inventory issues into their modeling .Koc et al [8] were able to use machine learning techniques to predict cost effects in construction projects, but this technique was not utilized in a CSC. Since predicting carbon emissions and paying attention to environmental criteria is one of the goals of this study, Peng [9] used a non-linear model and genetic algorithm to predict the amount of carbon emissions in the construction industry. However, it should be noted that their model was non-linear, and as a result, the results of this study cannot be fully assured, as non-linear models do not always provide the optimal global solution.

One way to control CSC costs and manage resources is to utilize existing strategies in the field. There are two resource delivery strategies in inventory control: Single Setup Single Delivery (SSSD) and SSMD. These two strategies operate differently due to their varying responses to storage and transportation costs [10]. The SSMD strategy involves receiving resources multiple times, which increases transportation costs but lowers holding costs. Factors such as the availability of financial resources and the nature of the project are crucial in selecting the optimal strategy [10]. To select the right strategy, it is crucial to carefully examine and analyze these factors. However, this method alone cannot effectively manage the costs of the chain. It is crucial to determine the period when the NPV for the system is at its most optimal state to achieve the goals of the present study. Additionally, choosing a supplier that excels in distance, quality, timely delivery, and price will be more effective in advancing the goals of CSC, so this should also be taken into consideration. Moreover, to comply with environmental considerations and reduce carbon emissions in the transportation of resources by vehicles to projects, it is necessary to conduct the study from this perspective. There have been numerous studies on SC design, primarily focusing on manufacturing industries (see, for example, [11, 12]). However, the construction industry, with its specific characteristics such as project-oriented nature, high demand variability, and supplier diversity, faces complexities that have been overlooked in existing models. Additionally, many previous studies have examined single-objective or deterministic conditions, which do not reflect the realities of construction projects. Addressing this gap, the present study introduces a multi-objective and uncertainty-based model for CSC design to facilitate more realistic and comprehensive decision-making. While the model is developed based on theoretical concepts, its structure is adaptable for application in real construction projects. The model parameters are defined using common industry indicators and tested with simulated scenarios that mirror operational conditions. Moreover, the decision-making challenges highlighted such as supplier selection (SS), resource allocation, sustainability considerations, return on investment, and cost considerations are common issues in the CSC that are prevalent in real-world settings. Consequently, the proposed model shows significant potential for implementation in industrial environments. Although numerous studies have been conducted in the field of CSC (for example, see [13, 14]), many of these studies have not taken a multi-objective and comprehensive approach. The present study, utilizing the Augmented Epsilon-Constraint (AEC) approach and novel solution techniques, aims to overcome these limitations and present an approach that is distinct from previous works. The purpose of this paper is to address the research gap and provide answers to the following Research Questions (RQs): RQ1) How can NPV and inventory control strategies be integrated to collaboratively design a CSC network? RQ2) What is the impact of NPV on the performance of a CSC? RQ3) How do the SSMD strategies impact the design of a CSC network? RQ4) How can the effect of a carbon tax on the model be investigated?

This study introduces a MINLP model to address the RQs by optimizing the design of a CSC. The model considers the time value of money to determine the most optimal period that maximizes NPV while minimizing deviations from the project budget. Additionally, it takes into account environmental criteria and carbon tax reduction. The model focuses on efficiently transporting resources from suppliers to project construction centers and selecting suppliers that can meet the required efficiency standards. Given the multi-objective nature of the presented mathematical model, it is crucial to select a precise solution method capable of extracting the complete and accurate front. The Pareto front refers to a set of solutions where no solution exists that can achieve one objective without compromising another. This concept forms the basis for decision-making analysis in multi-objective issues and aids in understanding the trade-offs between costs. In this context, the Enhanced ε-Constraint Method is utilized as an accurate and efficient approach to solving multi-objective optimization problems. This method enables the generation of a set of Pareto solutions by transforming all objective functions (OF), except one, into constraints and implementing epsilon control constraints. The enhanced version of this method stands out for its ability to prevent suboptimal and repetitive solutions, ensuring a more even coverage of the Pareto front. This feature assists decision-makers in analyzing the trade-offs between objectives more effectively. Thus, employing this method can significantly enhance the decision-making process in complex and multi-criteria environments, such as CSC design.

The contributions of this research can be explained in four main axes as follows:

- Cost reduction and analysis of the effects on NPV: The most important innovation of this research is the provision of an integrated framework for cost reduction along with the analysis of the effects of key variables on the calculation of NPV. To the best of the authors' knowledge, this is the first study that simultaneously addresses the selection of inventory control strategies in a CSC to reduce costs, reduce carbon emissions, and select the optimal supplier.
- Creating a balance between conflicting objectives: This research makes a significant contribution to the literature by identifying and modeling the trade-offs between different criteria, such as maximizing NPV, reducing carbon emissions, and SS. This balance has been less explored in previous studies.
- Selecting the appropriate timeframe for project implementation: Another innovation of this study is to consider selecting the optimal timeframe for project completion to maximize NPV. In previous research, this aspect was neglected and the method proposed in this study will reduce deviation from the project budget.

The remainder of the paper is structured as follows: Section 2 provides a comprehensive analysis of existing research gaps following a meticulous review of the relevant literature. The problem statement and formulation of the problem are presented in Section 3. Solution Methodology is presented in Section 4. Section 5 focuses on a numerical example and analysis of solution results. The policymaking is provided in Section 6, and the discussion is finally reported in Section 7.

2. Literature Review

The literature emphasizes the importance of adopting a strategic and holistic approach to CSC management. This approach should consider environmental factors and prioritize cost efficiency to effectively respond to the specific demands and constraints of construction projects. As discussed in the preceding section regarding the focus of the current study, this section is divided into three parts to review previous studies related to this topic.

2.1. Constructionand Inventory Control

Since adequate monitoring of inventory control is crucial for cost management, Joshi and Gupta [15] addressed this issue in their study. On the other hand, identifying optimal strategies for managing building materials is also necessary in the context of resource inventory control in the construction industry, leading Nerkar [16] to address this issue. Abbaspour et al[17]investigated integrated queuing, efficient routing, and inventory management in a green two-channel SC.Off-site construction, which has faced challenges in recent years, is another issue that requires investigation. Salari et al [18] used control models for optimal management considering stochastic demand. Mohammadnazari, Z. and S.F. Ghannadpour [19] also emphasized the importance of reducing the environmental effects caused by the transportation of materials in the construction industry and included this environmental dimension in their work. The Economic Order Quantity (EOQ) model is one method that can be used to determine the reorder point, but it has limitations. Kulkarni and Halder [20] used an outlier-based simulation model to determine order values. In another study by Golpîra [21], a model was presented that could provide dynamic resources. On the other hand, the tendency of academics and professionals towards CSC has increased. However, no review of recent research has been conducted so far with an emphasis on mathematical modeling and optimization approaches. In their study, [1] reviewed the concept of construction supply chain.

2.2. Construction and Time Value of Money

Since the wheel of development in Egypt and many other similar countries has been hindered by a lack of government funding, Kamel et al. investigated the behavior of NPV in construction projects in this country. The variability of the NPV allows for the evaluation of project efficiency under random conditions, prompting Kamel [22] to further investigate this issue. Kebriyaii [23] also introduced a multi-objective mathematical planning model to tackle scheduling challenges that involve balancing time, cost, and quality considerations within construction projects. One method for estimating NPV is the random method, which led Kasprowicz [24] to utilize this approach to evaluate project profitability under random execution conditions. Timing is a crucial factor in NPV calculations, prompting Grossman [25] to address timing issues and NPV calculations using a tree model. Given that specific present value is utilized to assess the financial performance of companies, Kipkiruiand Kimungunyi [26] focused on calculating the financial performance of companies within the cement industry. To maximize NPV, Rostami [14] successfully implemented dynamic policies to maximize project NPV, considering the uncertainties surrounding activity durations.

2.3. Construction and Carbon emissions

The construction sector is a major contributor to carbon emissions in China. Developing an effective and intelligent regression model based on machine learning algorithms to forecast carbon emission trends is challenging. Zhang et al [13] examined crane emissions and per capita indicators of the construction sector in 30 provincial regions of China from 2005 to 2021. Climate change is one of many issues that have raised awareness about achieving and improving net zero carbon emissions. On the other hand, to simplify the process of quantifying carbon emissions, there is a need for practical guidance on measuring the life cycle carbon emissions of buildings. Therefore, Lai et al [27] conducted a systematic review using the PRISMA method, which highlighted the challenges in quantifying carbon emissions. They suggested that these challenges can be overcome by identifying appropriate solutions through the integrated use of digital technologies, such as modeling. Building Information Modeling, Internet-of-Things, and Blockchain technology can all be considered. Since carbon emission reduction has become an environmental issue in the context of a low-carbon economy, Wang et al [28] studied and analyzed carbon emission reduction in CSC using differential game theory and MATLAB software. In addition to several other articles dealing with carbon dioxide emissions in construction, Karlsson et al [29] emphasized the importance of exploring alternative carbon emission policies. They specifically focused on carbon capture and the use of hybrid and electric construction machinery for heavy transport as strategies to mitigate carbon dioxide emissions. Wang et al [30] also highlighted the significance of examining the role of carbon tax as a deterrent policy. They suggested that behavioral and incentive policies, which promote awareness and voluntary adoption of low-carbon practices in the prefabricated building SC, should be considered. Additionally, they noted the limited effectiveness of carbon tax in the early stages of development.

Table 1summarizes the most important aspects. None of the previous studies have examined the time value of money alongside material inventory control with SSMD, highlighting the importance of investigating these aspects. Therefore, this study aims to design a CSC to minimize deviations from the project budget, consider the time value of money, and improve inventory management in distribution centers using SSMD. Additionally, a comprehensive study that includes reducing carbon emissions, in addition to the aforementioned cases, is important. From the perspective of selecting the appropriate model, a review of the previous literature has presented a wide range of optimization models for CSC design. Some of these studies are classical models such as EOQ and lot-sizing models. However, these models are unable to capture the complexity of real-world problems. Other studies have utilized Mixed Integer Programming(MIP) models, which can handle discrete constraints, but struggle with nonlinear constraints. Additionally, stochastic models, binary trees, differential games, and dynamical system approaches have been employed to simulate interactions between perturbed factors. In contrast, the approach presented in this study is based on MINLP, allowing for simultaneous discrete and continuous decision-making within a complex nonlinear framework. This unique feature enables the modeling of more complex constraints and relationships with greater accuracy. Given the nature of construction projects that involve an inventory of building materials, variables like order quantity and carrying capacity often include nonlinear constraints. Therefore, this approach offers high accuracy and flexibility compared to previous methods.

Table 1. A review of previous literature

Reference	Model	Delivery Types	Construction	Time of Value Money	SS	Environmental Restrictions	Model Types		Number of Objectives		Solution Method		Key Decisions	
							Liner	Non-Liner	Single	Multiple	Exact	Non-Exact	Decisions	Objectives
Salari, Mahmoudi [18]	EOQ	SSSD	✓				✓		✓			✓	Order Quantity	Min Cost
Kulkarni and Halder [20]	EOQ	SSSD	✓				✓		✓			✓	Order Quantity	Min Inventory
Hsu, Aurisicchio [31]	Stochastic		✓				✓		✓		✓	✓	Production Rate	Min Cost
Mohammadnazari and Ghannadpour [19]	MIP	SSSD	✓			✓	✓		✓		✓		Order Quantity	Min Cost
Fu and Xing [32]	MIP		✓				✓		✓			✓	Order Quantity Order Time Delivery Rate	Min Cost
Golpîra [21]	MIP		✓				✓		✓		✓		Material Carrying Amount	Min Cost
Ma, Yan [33]	Bi-level		✓					✓	✓			✓	The quantity of distributed materials	Min Cost
Kebriyaii, Heidari [23]	MIP		✓	✓			✓			✓		✓	Resource costs & Project worth	Project Scheduling & Cash Flow
Kasprowicz, Starczyk-Kołbyk [34]	Randomized method		✓	✓				✓	✓			✓	Random Variable of Project Overall Revenue, Project Cost & NPV	NPV of Project Efficiency
Grossman, Brazil [25]	binary rooted tree		✓	✓				✓	✓		✓		Topology and Approximate Geometry	Maximize NPV

Reference	Model	Delivery Types	Construction	Time of Value Money	SS	Environmental Restrictions	Model Types		Number of Objectives		Solution Method		Key Decisions	
							Liner	Non-Liner	Single	Multiple	Exact	Non-Exact	Decisions	Objectives
													& Schedule	
Kipkirui and Kimungunyi [26]	descriptive		✓	✓			✓		✓		✓		The cash inflows and outflows & discount rates	Effect of NPV
Hussain, Khalid [35]	NP-hard		✓	✓		✓		✓		✓		✓	Execution of an activity	Optimizing NPV and Greenhouse Gases
Rostami, Creemers [14]	MIP		✓	✓			✓		✓		✓	✓	Duration & Starting time	Max NPV
Zhang, Sun [13]	Regression model		✓			✓		✓				✓	Carbon Emissions	Predict carbon emission trends and promote carbon reduction policies
Lai, Abdul Rahiman [27]	Systematic Review (PRISMA)		✓			✓							Quantification process	Quantifying carbon emissions
Wang, Hao [28]	Differential game model		✓			✓		✓				✓	Centralized decision-making, Decentralized decision-making, and the introduction of cost-sharing contract	Carbon emission reduction
Karlsson, Rootzén [29]			✓			✓	✓				✓		Climate impact calculations &	Reducing the climate impact of road construction
Wang, Du [30]	Game-based system dynamics model		✓			✓				✓		✓	Major variables influencing carbon emission reduction level	Explore the effect of low-carbon practices
Proposed Model	MINLP	SSMD	✓	✓	✓	✓		✓		✓	✓	✓	Available Inventory, number of deliveries, quantity of orders,shortage, NPV, number of periods	Min cost Max Quality Min Delivery

3. Problem Statement

This study focuses on designing a two-level SC network in the construction industry (Figure 1). The first level of this project includes suppliers, and the second level includes the project site. Temporary facilities that aim to store and pre-process resources are located near the project site, so these facilities are considered to be on the same level as the project site. Suppliers provide the resources required for the project, making the selection of the right supplier crucial for facilitating the project implementation process. Therefore, SS criteria such as price, capacity, distance, and quality are discussed in this study. By including these criteria in the problem formulation, along with other conditions governing the problem, the most suitable supplier can be selected. The right resources for project implementation must be delivered on time to ensure the project can be completed as scheduled. Deviations from the resource delivery schedule by suppliers should be addressed, and these deviations should be included in the modeling. Additionally, environmental considerations, such as reducing carbon dioxide production, should be taken into account when transporting resources. Carbon emission policies, like the carbon tax, are implemented in the modeling to address these environmental concerns. Minimizing the total costs of designing the SC is another crucial aspect that should be considered. All costs associated with the SC design should be carefully analyzed and minimized to ensure efficiency and cost-effectiveness.

Managing project budgets is crucial in construction projects to ensure appropriate investment from an economic perspective. On the other hand, the economic justification of a project is closely related to minimizing deviations from the project budget. Identifying the economic nature of a project can indicate its profitability. In this research, the ROR on investment is used to justify the economic viability of a project, which is crucial in evaluating its profitability. To include this rate in the calculations, the NPV must be calculated. The expression $SST_t = \frac{1}{(1+ROR)^t}$, which represents the coefficient of the present value of a single payment multiplied by the terms of costs related to t, allows the calculation of NPV for the base year. In engineering economics, a positive NPV indicates an economic project, while a negative NPV indicates an uneconomic project. Therefore, it is necessary to calculate NPV. Based on these explanations, the cost OF, which includes the budget concept, is proposed to minimize deviations from the project budget. Other assumptions of this study include: The time horizon is considered limited and discrete due to the nature of construction projects, which will be completed. The demand is considered discrete and certain, with values estimated before the project begins.

1. A specific transportation mode is selected.
2. Important variables in this study include determining the frequency of shipments, the quantity of each shipment, and addressing shortages.
3. Due to the importance of reducing carbon emissions, a strict carbon restriction policy has been implemented in this study. This policy ensures that any excess emissions of greenhouse gases are subject to a penalty in the form of a carbon tax. Therefore, this factor has been included in the calculations.
4. If the inventory of resources is insufficient to fully meet demand in a given period, the shortage is recorded in the system as a backlog. This shortage represents unmet demand that has occurred due to insufficient inventory or delays in shipments from suppliers and must be made up in future periods. Therefore, the shortage of materials is not considered a lost demand, but rather a deferred requirement that affects the inventory required in subsequent periods. This assumption allows the model to track the cumulative effect of shortages over time and to factor them into ordering and resource allocation decisions in subsequent periods.

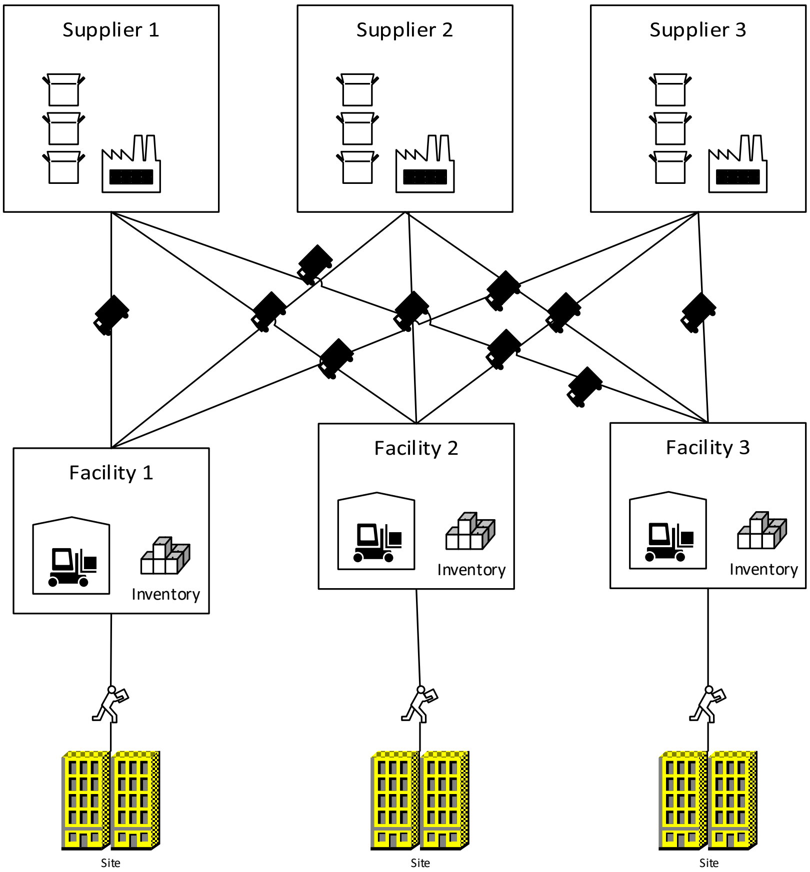

Figure 1. CSC network design

3.2. Mathematical Model

In this first part, the indices, parameters, and variables of the current problem were described to ensure a clear understanding. Following this, the Objectives and constraints of the problem were explained.

Index:

OF_1, OF_2, OF_3	Index for each OF
$s \in S$	Set of suppliers
$f \in F$	Set of distribution centers(facilities)
$p \in P$	Set of projects
$t \in T$	Set of periods
$r \in R$	Set of resources
$o \in O$	Transportation mode index

Decision Variables:

Θ_{frtp}	The binary variable indicating whether facility *f* transports resource type *r* to project *p* at time *t* or not
γ'_f	Binary variable devoted to defining whether facility *f* is opened
γ''_p	Binary variable devoted to defining whether project *p* is opened
ρ_{rsft}	A binary variable that indicates whether resource *r* is transported by supplier *s* for facility *f* in period *t* or not.
$\eta_{r,s,f,t,o}$	The number of times that resource type *r* is delivered from supplier *s* in period *t* for facility *f* using transportation mode *o*.
ℓ^{+}_{rft}	The available inventory (non-negative) of resource type *r* at facility *f* at the end of period *t*.
ℓ^{-}_{rft}	The remaining shortage quantity of resource type *r* at facility *f* at the end of period *t*.
Λ_{rsfto}	The quantity of each sends of resource type *r* from supplier *s* and transported to facility f in period *t* using transportation mode *o*.
$\mathfrak{H}'_{rsfto}$	The shortage shipments of resource type *r* delivered from supplier *s* to facility *f* in period *t* using transportation mode *o*.
$\mathfrak{R}''_{fp}$	The binary variable indicating whether facility *f* transports resources to project *p* or not
$\mathfrak{R}'_{ftp}$	The binary variable indicating whether facility *f* transports resources to project *p* at time *t* or not
$\mathfrak{R}'''_{sfo}$	The binary variable indicates that the mode of transport *o* between supplier *s* and can be selected.

Parameters:

$\mathcal{F}''_{sf}$	The distance between supplier *s* and facility *f*
M	A very large positive number
ϖ_{rs}	The latest delivery date for resource *r* from supplier *s*
$\mathbb{C}_s$	Capacity of supplier *s*
$\mathbb{C}'_f$	Capacity of facility *f*
$\mathbb{C}''_{sfo}$	Capacity of transportation mode *o*between supplier *s* and facility *f*
$\mathbb{C}'''_p$	Capacity of project *p*
$\aleph_{rst}$	The minimum acceptable order quantity for resource type *r* from supplier *s* in the period *t*
γ_{rsft}	The percentage of defective resources of type *r* procured by supplier *s* for facility *f* in the period *t*
β''_f	Fixed cost of opening facility *f*
β'''_p	Fixed cost of opening project *p*
β^{Fx}_{fp}	The fixed cost of allocating facility *f* to project *p*
β^{Tr}_{rsfto}	The unit transportation cost for resource type *r* from supplier *s* to facility *f* in time period *t with* mode *o*
$\beta^{Holding}_{rft}$	The unit holding cost for resource type *r* at facility *f* in time period *t*
β^{π}_{rft}	The cost of shortage per unit of resource *r* for facility *f* in time period *t*
β^{TAX}	The carbon tax rate per unit
$\mathcal{E}_f$	Carbon emission in kg(*f*)
$\mathcal{E}_p$	Carbon emission in kg(*p*)
$\mathcal{E}_{sfo}$	Carbon emission in(kg/unit) of shipping products between suppliers and facilities using O^{th} transportation mode
$\beta^{purchase}_{rst}$	The purchase price of resource type *r* from supplier *s* in time period *t*
$\beta^{Ordering}_{rsf}$	The Ordering cost for resource *r* from supplier *s* for facility *f*
$Budget_P$	The total budget of project *p*
$U\varpi_{rs}$	The maximum upper bound for the latest delivery date for resource *r* from supplier *s*
$C\varpi_{rs}$	The unit penalty cost incurred if resource *r* from supplier *s* falls between $H_{rs}$and UH_{rs}
Ψ_{rs}	The earliest delivery date for resource *r* from supplier *s*
$L\Psi_{rs}$	The minimum lower bound for the earliest delivery date for resource *r* from supplier *s*
$C\Psi_{rs}$	The unit penalty cost incurred if resource *r* from supplier *s* falls between $L'\Psi_{rs}$and Ψ_{rs}
L'_{rs}	The lead time for resource *r*, delivery by supplier *s*
Δ_{rft}	The quantity of demand for facility *f* in period *t* for resource *r*

The model presented in this study can be formulated using Equations (1) to (22).

$$P'=(\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\times\beta_{rst}^{purchase}\times SS_t+\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\beta_{rsfto}^{Tr}\times\eta_{r,s,f,t,o}\times\Lambda_{rsfto}\times\mathcal{F}''_{sf}\times SS_t+\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\beta_{rsf}^{ordering}\times\rho_{rsft}\times SS_t+\sum_{f=1}^{F}\beta''_f\,\gamma'_f+\sum_{f\in F_p}\sum_{p=1}^{P}\Re''_{fp}\times\beta_{fp}^{FX}+\sum_{r=1}^{R}\sum_{f\in F_p}\sum_{p=1}^{P}\sum_{t=1}^{T}\beta_{rft}^{\pi}\times\ell_{rft}^{-}\times SS_t+\sum_{f=1}^{F}\beta'''_p\,\gamma''_p+\sum_{r=1}^{R}\sum_{f\in F_p}\sum_{p=1}^{P}\sum_{t=1}^{T}\beta_{rft}^{holding}\times\ell_{rft}^{+}\times SS_t+\beta^{TAX}(\sum_{f=1}^{F}\mathcal{E}_f\,\gamma'_f+\sum_{p=1}^{P}\mathcal{E}_p\,\gamma''_p+\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\mathcal{E}_{sfo}\times\Lambda_{rsfto}\times\eta_{r,s,f,t,o})) \tag{1}$$

$$\text{Min}(Budget_p - P') \tag{2}$$

$$\text{Max } Quality = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\eta_{r,s,f,t,o}\times\Lambda_{rsfto}\times(1-\gamma_{rsft}) \tag{3}$$

$$\text{Min } Penalty = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\eta_{r,s,f,t,o}\times\Lambda_{rsfto}\times C\Psi_{rs}(\Psi_{rs}-L'_{rs})+\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{o=1}^{O}\eta_{r,s,f,t,o}\times\Lambda_{rsfto}\times C\varpi_{rs}\times(L'_{rs}-\varpi_{rs}) \tag{4}$$

$$\sum_{f\in F_p}\Re''_{fp}=1,\forall p \tag{5}$$

$$\sum_{p=1}^{P}\Re''_{fp}=1,\forall f \tag{6}$$

$$\Theta_{frtp}=\Re'_{ftp} \quad \forall f,r,t,p \tag{7}$$

$$\sum_{s=1}^{S}\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\geq\Delta_{rft} \quad \forall r,f,t \tag{8}$$

$$\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\geq\varkappa_{rst}\times\rho_{rsft} \quad \forall r,s,f,t \tag{9}$$

$$\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\leq\rho_{rsft}\,M \quad \forall r,s,f,t \tag{10}$$

$$\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{o=1}^{O}\Lambda_{r,s,f,t,o}\times\eta_{r,s,f,t,o}\leq M\sum_{p=1}^{P}\Re''_{fp} \quad \forall f \tag{11}$$

$$\ell_{rft}^{+}=\ell_{rf(t-1)}^{+}+\sum_{s=1}^{S}\sum_{o=1}^{O}\Lambda_{r,s,f,t,o}\times\eta_{r,s,f,t,o}-\sum_{s=1}^{S}\sum_{o=1}^{O}\mathfrak{H}'_{rsfto} \quad \forall r,f,t \tag{12}$$

$$\ell_{rft}^{-}=\ell_{rf(t-1)}^{-}+\Delta_{rft}-\mathfrak{H}'_{rsfto} \quad \forall r,s,f,t,o \tag{13}$$

$$\mathfrak{H}'_{rsfto}\leq\ell_{rf(t-1)}^{-} \quad \forall r,s,f,t,o \tag{14}$$

$$\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\leq\rho_{rsft}\times\mathbb{C}_s \quad \forall r,s,f,t \tag{15}$$

$$\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{o=1}^{O}\Lambda_{rsfto}\times\eta_{r,s,f,t,o}\leq\mathbb{C}'_f\times\gamma'_f \quad \forall f \tag{16}$$

$$\sum_{r=1}^{R}\sum_{f=1}^{F}\sum_{t=1}^{T}\ell_{rft}^{+}\leq\mathbb{C}''_p\times\gamma''_p \quad \forall p \tag{17}$$

$$\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{f=1}^{F}\Lambda_{r,s,f,t,o}\times\eta_{r,s,f,t,o}\leq\mathbb{C}''_{sfo}\times\Re'''_{sfo} \quad \forall s,f,o \tag{18}$$

$$\sum_{o=1}^{O}\Re'''_{sfo}\leq\gamma'_f \quad \forall s,f \tag{19}$$

$$\rho_{rsft}\times L'_{rs}\leq U\varpi_{rs} \quad \forall r,s,f,t \tag{20}$$

$$\rho_{rsft}\times(L'_{rs}-L\Psi_{rs})\geq 0 \quad \forall r,s,f,t \tag{21}$$

$$\Re''_{fp},\Re'_{ftp},\Theta_{frtp},\rho_{rsft},\gamma'_f,\gamma''_p,\Re'''_{sfo}\in[17],\eta_{r,s,f,t,o}\in integer \quad \ell_{rft}^{+},\ell_{rft}^{-},\mathfrak{H}'_{rsfto},\Lambda_{rsfto}\geq 0 \tag{22}$$

Equation (1) represents the total SC costs. To further explain each component of this equation, the following will outline how to calculate each cost. The purchase cost of each order is determined by multiplying the purchase unit price by the order quantity ($\Lambda_{r,s,f,t,o} \times \eta_{r,s,f,t,o}$). Similarly, the costs of ordering, holding, shortage, and transportation are calculated by multiplying the corresponding quantity of the order by their unit costs. The transportation cost calculation includes the consideration of transportation distance as a significant parameter affecting the cost. When calculating the allocation cost, it is crucial to determine whether the facility or project location is allocated. The allocation cost is derived from the product of the binary allocation variable and the corresponding allocation cost. The final cost is determined by the carbon tax amount, which is calculated based on the product of the amount of carbon dioxide (or equivalent) emitted from the facilities and projects, as well as the emissions from transporting resources between the facility and suppliers, multiplied by the carbon tax rate. Equation (2) represents the minimization of the deviation of the total SC costs from the set budget. To maximize the quality of the resources provided, equation (3) has been introduced. Since a percentage of resources may be defective, this percentage (γ_{rsft}) has been subtracted from the total amount of resources received. This allows us to focus solely on maximizing the quality of the resources. Equation (4) was created to minimize deviations from supplier delivery schedules. Resources are deemed acceptable if they are delivered within these specified timeframes. Any resource delivered before Ψ_{rs} or after ϖ_{rs} will be rejected and returned to the supplier. However, resources delivered between $\Psi_{rs}$and $L\Psi_{rs}$, as well as$\varpi_{rs}$and $U\varpi_{rs}$, will be accepted by the supplier with a penalty [36]. Only one facility should be assigned to one project, as per the restrictions in equations (5) and (6), which are also applicable. Using equation (7), a resource must be transported through the selected facility. Equation (8) is formulated to determine the demand values for each resource. The minimum order quantity required for each supplier is indicated by equation (9). The order values are positive when the corresponding binary variable is set to 1, as indicated by equation (10). Appropriate amounts of resources must be transferred through reliable facilities, as indicated by equation (11). Equation (12) determines the available inventory of material *r* at facility *f* at the end of period *t*. This inventory includes the remaining amount from the previous period ($\ell^{+}_{rf(t-1)}$) that may not have been consumed due to reasons such as contractor inactivity. On the other hand, the ordered quantity for each resource in each period ($\Lambda_{r,s,f,t,o} \times \eta_{r,s,f,t,o}$), which is determined based on pre-project planning, affects the inventory level. Additionally, the possible shortage ($\mathfrak{H}'_{rsfto}$) due to insufficient shipment of materials by suppliers is deducted from the available inventory. Therefore, equation (12) is modeled to account for these factors.The amount of backlog shortage is equal to the difference between the actual demand and the amount of resources available in the same period, provided that this value is positive. In other words, whenever the supply of resources is less than the demand, the shortage created is recorded as a backlog and carried over to subsequent periods for compensation. It is crucial to include this value in the model and formulate it mathematically. Consequently, constraint (13) is defined to ensure that the amount of backlog for each resource at the end of each period is equal to the backlog from the previous period, plus the demand for that resource in the current period, minus the shortage of that resource in the same period. Constraint (14) ensures that, in each period, at most, the remaining orders from the previous period will be delivered. The capacity of each supplier is defined by Equation (15). Equation (16) limits the capacity of each distribution center. Constraint (17) represents the limitation of the capacity for each project within a specific period. Equation (18)specifies the transportation capacity of different resource transport modes. Equation (19) represents the relationship between transportation from facility *f* to supplier *p*. In other words, the transport flow occurs when facility *f* is operational. The maximum time for the delivery of resources by suppliers is determined by the equation (20). In general, the delivery time should not be earlier than the minimum delivery time limit indicated by equation (21). The range of variables is represented by the constraint (22).

4. Solution Methodology

The optimal solution in optimization problems is typically defined as the solution that fully optimizes a specific objective and cannot be improved by any other change. However, in multi-objective problems where different objectives conflict, finding a single optimal solution is challenging, leading to the search for Pareto-optimal solutions. These solutions are selected in a way that no solution can be improved without negatively impacting other objectives [2]. Exact methods such as the Weighted Sum Method (WSM) and the epsilon constraint are utilized to find Pareto-optimal solutions in these cases. In the Weighted Sum Method (WSM), each objective is assigned a weight, but this approach may not accurately express preferences[3]. On the other hand, the epsilon constraint method is more flexible, as it constrains each objective separately, allowing for better coverage of the Pareto front. The AEC method offers more benefits than the traditional version because the parameter ε is dynamically adjusted, resulting in a more uniform and comprehensive coverage of the Pareto front. This method enhances the accuracy and diversity of solutions, particularly in complex problems, by intelligently adjusting parameters and effectively distributing solutions. Considering the nature of the studied problem, which is multi-objective and non-linear, the authors explored various methods. They concluded that the AEC method is a precise approach for solving multi-objective models. Previous studies [37, 38] have also endorsed this method. Therefore, the AEC method is deemed suitable for addressing the model presented in this study. The following is a detailed explanation of this method.

Initially, each OF is assigned a unique index (e.g., Of_1, Of_2, Of_3) to differentiate between them, such as cost, time, or quality. In case of maximization functions, they are converted to minimization form by multiplying by a negative number to ensure consistency in evaluation. Subsequently, a Payoff Table is constructed, with the main diagonal containing optimal values of each function when optimized individually, and other cells containing worst-case values encountered when optimizing another function. Typically, cost is the primary OF, as cost-effectiveness is crucial for acceptability. The remaining OFs are constrained by an epsilon value, which must be precisely met, not just approached. To enforce this condition, a Slack value is introduced and incorporated into the main OF using a coefficient, *Phi*. For each function, the minimum, maximum, and range of its values are calculated to determine appropriate *Phi* coefficients and Step Size. *Phi* coefficients are derived from the ratio of the range of the first function to the second. Epsilons begin at the minimum value of the corresponding functions and increment in regular intervals. Each change in epsilon yields a new solution on the Pareto front, representing optimal solutions across different criteria. By iteratively adjusting epsilon values and obtaining new solutions within a specified number of iterations (iter) (e.g., 10 times), a set of optimal solutions can be generated, analyzed, or displayed.

5. Analysis of Results

In this section, the MINLP problem presented in this study has been coded for different sizes using GAMS. The simulations were run on an Intel(R) Core(TM) i5-1035G1 processor with a frequency of 1.00 GHz and 4 GB of memory. Since the model is a MINLP, appropriate solvers should be used to solve it in this software environment. According to the [39] Solver Baron study, it is introduced as one of the most advanced and accurate solvers for nonlinear and nonconvex optimization problems. This solver, using a combination of convex relaxations, branch-and-bound, and intelligent preprocessing techniques, can solve very complex continuous and discrete problems with guaranteed global optimal solutions. Therefore, BARON is a very suitable solver for complex, especially nonlinear, models due to its high accuracy, wide model coverage, and ability to guarantee global optimal solutions. Therefore, the authors used this solver in this study. To solve the model, input parameters are required. The input parameters and dimensions of the problem are presented in Tables (2) and (3). After that, the model is solved for all sizes of the current problem, and the results are shown in Table (4). It can be observed that as the size of the problem increases, the time taken also increases significantly. The Baron solver was unable to solve the problem within the set execution time of 7200 seconds. Therefore, the model is linearized to determine if the solution in this state can effectively address the current issue.

To linearize nonlinear relationships using linear constraints, Big-M methods [40] can be employed to transform nonlinear expressions into linear equivalents. In certain cases of MIP models, it becomes necessary to convert nonlinear relationships, such as products of integer variables, into linear relationships. In this context, relationships (23) to (27) are utilized, where M' represents a sufficiently large number used to ensure the validity of constraints under various conditions. The primary objective of this section is to substitute nonlinear expressions with linear equivalent relationships, which are elaborated upon below. Relationship (23) is a nonlinear relationship that entails the multiplication of an integer variable by a positive variable.

$$\Lambda_{rsfto} \times \eta_{r,s,f,t,o} = \varphi_{r,s,f,t,o} \tag{23}$$

To linearize this relationship, constraints (24) through (26) are utilized.

$$\varphi_{rsfto} \geq \eta_{r,s,f,t,o} - M'(1-\Lambda_{rsfto}) \tag{24}$$

$$\varphi_{rsfto} \leq \eta_{r,s,f,t,o} + M'(1-\Lambda_{rsfto}) \tag{25}$$

$$\varphi_{rsfto} \leq M'\Lambda_{rsfto} \tag{26}$$

The constraints above ensure that if $\Lambda_{rsfto} = 1$, the value of φ_{rsfto}will be equal to $\eta_{r,s,f,t,o}$, and if Λ_{rsfto}= 0, the value of φ_{rsfto} will be zero. This linearizes the original nonlinear relationship using a set of linear constraints, making it suitable for use in integer linear programming models. This method is one of the most common techniques for linearizing product expressions of decision variables.

Table 2. Problem Data Generation based on the actual behavior of the construction company

Parameter	Δ_{rft}	β''_f($)	$\beta^{Holding}_{rft}$($)	β^{π}_{rft}($)	β^{Fx}_{fp}($)
Value	uniform (25,100)	uniform (300,800)	uniform (10,50)	uniform (5,50)	uniform (50,150)
Parameter	β^{Tr}_{rsfto}($)	$\mathcal{E}_{rsft}$	$\mathbb{C}'_f$	$\mathcal{F}''_{sf}(km)$	$\beta^{Ordering}_{rsf}$($)
Value	115	uniform (0,0.2)	uniform (1000,1300)	uniform (3,15)	uniform (10,15)
Parameter	$\aleph_{rst}$	$\mathbb{C}_s$	$\mathbb{C}''_{sfo}$	$\beta^{purchase}_{rst}$($)	$\mathbb{C}'''_p$
Value	uniform (10,25)	uniform (55000,70000)	1000	{3,3.2,3,3.1,3.4} {2,2.2,2,2.1,2.4} {5,5.2,5,5.1,5.4} {4,4.2,4,4.1,4.4} {7,7.2,7}	Uniform (900,1000)
Parameter	$\mathcal{E}_f$	$\mathcal{E}_p$	$\mathcal{E}_{sfo}$	ROR	C^{tax}
Value	uniform (3,4)	uniform (1,2)	uniform (7,7.5)	20%	0.6

The linear solution results of the model are shown in Table 5, which demonstrates that this model effectively solved the size 7 problem in 104 seconds. By comparing the model solution results in both scenarios, it can be concluded that the linearized model can solve the current problem with very little difference compared to the nonlinear model. For example, in the cost OF for different problem sizes in the nonlinear mode, we have the values 3.98423E+7, 3.91160E+7, 3.94619E+7, 3.87150E+7, 7.94508E+7, and 7.85666E+7. When solving the model in the linear mode, these values are 3.98423E+7, 3.91160E+7, 3.94619E+7, 3.87150E+7, 7.85678E+7, and 7.85673E+7. Therefore, the difference between the output of the first OF (Cost) for the two models is very small. The models also have a small difference in the output value related to minimizing the deviation from the project budget, specifically in terms of cost. However, the linear mode had times of 3, 3.7, 16.7, 12.3, 25, and 780, while the last unresolved cases in the nonlinear mode had times of 2.6, 3, 3.5, 4, 4.4, 42, and 104. From an accuracy standpoint, the difference between the two is imperceptible. However, in terms of time, the solution time in the linear method is much shorter and acceptable. Considering that it can solve the problem in a very short time, especially size 7, which cannot be solved by nonlinear methods at all, it can be inferred that the linearization of this model is justified because, in addition to the insignificant difference in the values of the first OF, the same is true for the second and third OFs.

Table 3. Other input parameter values depend on the size and dimension of the problem

Size	*R/S/F/P/T/O*	$\beta udget(p)$	ψ_{rs}	ϖ_{rs}	L'_{rs}	$L\psi_{rs}$	$U\varpi_{rs}$	$C\psi_{rs}$	$C\varpi_{rs}$
1	1/1/1/1/3/1	4×10^7	16	18	20	14	19	0.02	0.07
2	2/1/1/1/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\end{bmatrix}$
3	3/1/1/1/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\\13\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\\16\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\\17\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\\11\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\\17\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\\0.11\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\\0.19\end{bmatrix}$
4	4/1/1/1/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\\13\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\\16\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\\17\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\\11\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\\17\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\\0.11\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\\0.19\end{bmatrix}$
5	5/1/1/1/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\\13\\12.5\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\\16\\15.5\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\\11\\10.5\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\\0.11\\0.1\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\\0.19\\0.19\end{bmatrix}$
6	5/1/2/2/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\\13\\12.5\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\\16\\15.5\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\\11\\10.5\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\\0.11\\0.1\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\\0.19\\0.19\end{bmatrix}$
7	5/1/10/10/3/1	4×10^7	$\begin{bmatrix}16\\14\\13.5\\13\\12.5\end{bmatrix}$	$\begin{bmatrix}18\\17\\16.5\\16\\15.5\end{bmatrix}$	$\begin{bmatrix}20\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}14\\12\\11.5\\11\\10.5\end{bmatrix}$	$\begin{bmatrix}19\\18\\17.5\\17\\16.5\end{bmatrix}$	$\begin{bmatrix}0.02\\0.13\\0.12\\0.11\\0.1\end{bmatrix}$	$\begin{bmatrix}0.07\\0.18\\0.19\\0.19\\0.19\end{bmatrix}$

Table 4."OF Values Obtained from Solving the Nonlinear Model (for all sizes of the present problem)"

Size	Obj 1	Obj 2	Obj 3	CPU Time(s)
1	3.98423E+7	178.009	11.544	3
2	3.91160E+7	920.889	-263.038	3.7
3	3.94619E+7	459.401	-84.242	16.7
4	3.87150E+7	669.882	-141.937	12.3
5	7.94508E+7	1730.414	-412.445	25
6	7.85666E+7	8735.829	-2101.255	780
7	-	-	-	Do not Solve

Table 5. OF Values Obtained from Solving the Linear Model (for all sizes of the present problem) "

Size	Obj 1	Obj 2	Obj 3	CPU Time(s)
1	3.98423E+7	178.009	11.544	2.6
2	3.91160E+7	920.889	-263.038	3
3	3.94619E+7	459.401	-84.242	3.5
4	3.87150E+7	669.882	-141.937	4
5	7.85678E+7	1662.699	-393.912	4.4
6	7.85673E+7	8733.889	-2087.089	42
7	7.98480E+8	17446.991	-4014.634	104

After analyzing the results of the two models, particularly the first OF based on cost, and recognizing the crucial role of cost control in managing system costs, it is now time to examine the various types of SC costs in the implementation of the SSMD strategy. Figure 3 and Table 6 provide detailed explanations about these costs. The results indicate that transportation costs represent the largest portion of costs across all sizes, a direct outcome of adopting the SSMD strategy. As previously mentioned, in this strategy, transportation costs typically make up a significant portion of chain costs due to the multiple transportation of resources. Therefore, the results align with the strategic assumption of SSMD. Following transportation costs, the next significant expenses are associated with shortages. Given that shortages are permissible under this strategy, it is expected that these costs would be present, thus validating this assumption. Holding costs for all problem sizes are assumed to be zero, likely due to the direct correlation between holding costs and shortages. Despite shortage costs for all problem sizes, there is no inventory remaining to incur holding costs, affirming the model's accuracy. The values of the costs are depicted near the horizontal axis in Figure 2, indicating minimal values compared to the total cost. While cost analysis is an essential component of chain cost analysis, it is crucial to emphasize that comparing and analyzing costs should not be limited to the economic aspect of projects. It is vital to consider other factors that shape the economic or non-economic nature of a project. Therefore, examining NPV and its significant role in economic decision-making is essential.

An investment is considered profitable when it has a positive NPV. Therefore, among several investment options, a project with a positive NPV is economically preferable. To assess the profitability of projects with different scales, NPV values were examined under various RORs. The results of this analysis are presented in Table (7) and Figure (3). According to Figure (4), an increase in the ROR leads to an increase in the NPV value. Therefore, it can be concluded that as the ROR increases, the project's profitability also increases. It is important to note that the values chosen for the ROR in this analysis cover a reasonable and realistic range of possible rates of return in actual investment conditions. This range aims to evaluate the sensitivity of NPV to changes in the ROR and determine the thresholds at which the project becomes economically viable. Additionally, the selected range includes both conservative and optimistic values to provide a comprehensive assessment of project performance under varying financial conditions. This approach facilitates more accurate comparisons between projects with different cost structures and risk levels.

Table 6. The costs obtained for size number 3 to 7

Size	Total Inventory and Holding Cost (A)	Total Shortage Cost (B)	Total Transportation Cost (C)	Total Ordering Cost (D)	Total Fixed Cost(E)	Total Purchase Cost (F)	Total opening cost for facility (H)	Total opening cost for project (G)	Total cost of carbon tax(I)
3	0	16371.785	516817.646	113.025	61.049	1747.155	799.059	0	2180.169
4	0	27880.701	1250283.382	133.376	96.380	2690.245	681.125	0	3272.284
5	0	28125.492	1161860.984	189.391	126.996	4220.819	379.759	0	4250.050
6	0	54306.013	1360648.989	353.910	169.588	7842.015	1116.318	0	7802.871
7	0	255467.876	1086583.977	1873.921	856.892	39785.490	5125.229	0	42961.503

Table 7. ROR values against NPV for Size 1

RoR	16%	18%	20%	22%	24%
NPV ($Budget_p - P'$)	39898700	39903900	39908400	39913000	39917100

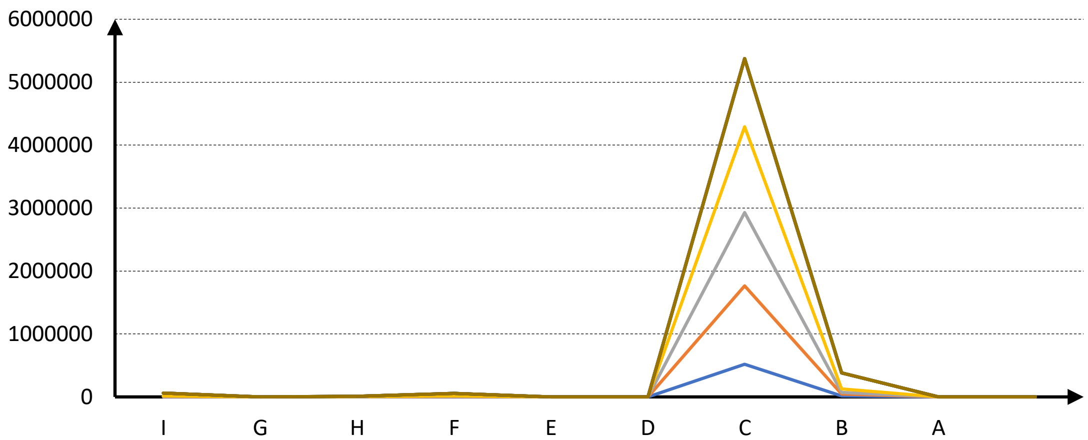

Figure 2. Chain costs by type for sizes 3-7

Another important sensitivity analysis in this section is to determine the number of periods in which the NPV is positive and higher. To calculate this, NPV values for problem size 1 and ROR 20% were calculated for periods 1, 2, and 3. It was found that NPV had the highest value in period 1. Therefore, completing the problem in question in one period is more economical than in the other periods (see Table 8 and Figure 4). In other words, it can be inferred that with an increasing number of periods, NPV values tend to decrease, so the fewer periods the project is implemented, the more economical it is. Having comprehensively examined the cost issue, the importance of inventory control and management, and determining the most economical project, it is now time to examine the impact of the carbon tax and its effect on the model. One aspect of consideration in the modeling of this study was the examination of carbon tax policy.

Considering the changes in the C^{tax} parameter and its effect on the model, since $C^{tax}$is a cost parameter, the value of the first OF was expected to change by 50% when running different simulations. It was observed that the change occurred in the first function (see Table (9) & Fig (5)). On the other hand, despite the positive impact of C^{tax}policy on cost reduction, this policy also has limitations. In this study, the amount of carbon emissions was not affected by the change in C^{tax}, indicating the limited effectiveness of this policy in actual pollution reduction, likely due to the rigid constraint in the model. Additionally, fluctuations in the solution time of the model at different C^{tax} levels can reduce computational efficiency. Cost reduction may be attributed to the shifting of costs between sectors rather than actual savings. Finally, the implementation of this policy in practice may be accompanied by economic and social challenges.

Table 8. Changes in the period on NPV (ROR = 20 % & Size 1)

T	T=1	T=2	T=3
NPV $(Budget_p - P')$	39966100	39915700	39908400

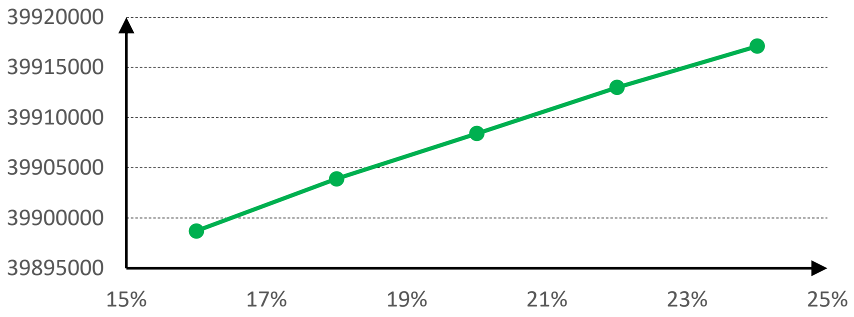

Figure 3. Trend of ROR values against NPV for size 1

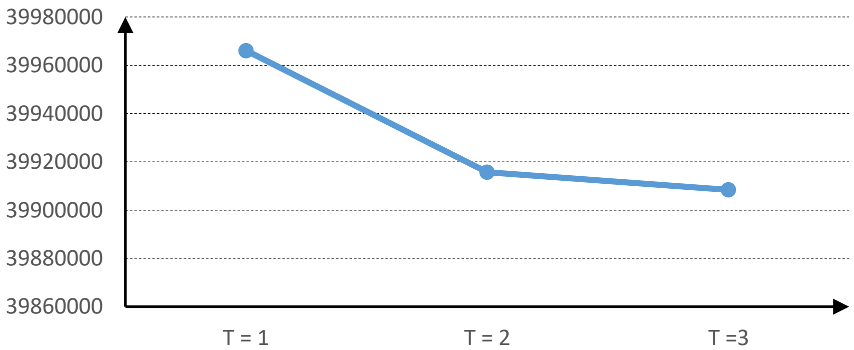

Figure 4. Trend of period values against NPV (ROR = 20% & Size 1)

Table 9. The OFs performance of the model against different values of parameter C^{tax} (Size 1)

C^{tax}	$(Budget_p - P')$	Quality	Penalty	Carbon Emission	Time(s)
0.3	39842700	178.009	11.544	1429.913	5.304
0.36	39842700	178.009	11.544	1429.913	3.096
0.42	39842600	178.009	11.544	1429.913	2.885
0.48	39842500	178.009	11.544	1429.913	2.979
0.54	39842400	178.009	11.544	1429.913	2.974
0.6	39842300	178.009	11.544	1429.913	2.853
0.66	39842200	178.009	11.544	1429.913	3.063
0.72	39842100	178.009	11.544	1429.913	2.783
0.78	39842100	178.009	11.544	1429.913	2.906
0.84	39842000	178.009	11.544	1429.913	2.896
0.9	39841900	178.009	11.544	1429.913	3.07

After analyzing the costs, it is now time to check the values of the key variables. Given the nature of the construction projects that need to be completed in the future, all resources must be provided until the end of the planning horizon. However, the assumptions allow for shortages, so the variables $\mathfrak{H}^{+}_{r,s,f,t,o}$, and $\ell^{-}_{r,f,t}$ were introduced for this purpose. Table (10) presents several multidimensional tables to accurately display the variables for the first size of the current problem. About the frequency and quantity of each sent value, two variables, $\eta_{r,s,f,t,o}$ and $\Lambda_{r,s,f,t,o}$, have been introduced (See (a) & (b)). For example, in the first period, 18.941 units will be sent from the resource in 2 shipments. Parts (c) and (e) shows that some resources are delivered late.

6. Policy Making

In the current era, policymaking is recognized as a key tool for managing and improving economic and environmental processes. In the field of construction, inventory control and Supply Chain Management (SCM) are important aspects that can be optimized to reduce costs and increase productivity. On the other hand, in today's world, it is necessary to pay attention to the reduction of carbon emissions and consider the NPV of projects as basic indicators in environmental and economic policies. This introduction examines these issues and emphasizes the importance of formulating policies that can provide maximum economic value for construction projects by optimizing inventory control and SCM, while reducing carbon emissions. In the following section, policymaking will be discussed.

- According to Table (6), transportation costs for each level of CSC with values (516817.646, 1250283.382, 1161860.984, 1360648.989 and 1086583.977) represent the highest percentage of total chain costs in all dimensions of the chain. This indicates that special attention is paid to this type of cost. Therefore, construction project managers need to pay special attention to this aspect when controlling their costs and simplifying cost management operations.
- With the increase in the ROR from 16 to 24 percent, the NPV also increased from 39,898,700 to 39,917,100. An increase in ROR usually indicates greater investment attractiveness, which often leads to an increase in the NPV of the proposed project or policy. Conversely, policies that can enhance this rate in investment projects will not only increase NPV but also be more appealing to investors. Therefore, special attention should be given to this solution in the evaluation of policy options as it will result in added economic value.
- As the project period extends from T = 1 to T = 3, the NPV value decreases (from 39,966,100 to 39,908,400). This issue becomes more noticeable when the discount rate is relatively high, as the value of future cash flows decreases significantly. From an investment standpoint, policies and projects should be structured to have the shortest possible payback period. Therefore, incentives to expedite implementation and reduce payback time should be considered to prevent the increase of administrative hurdles. Additionally, careful attention should be given to the project duration and the rate of decline in numerical NPV when making decisions.

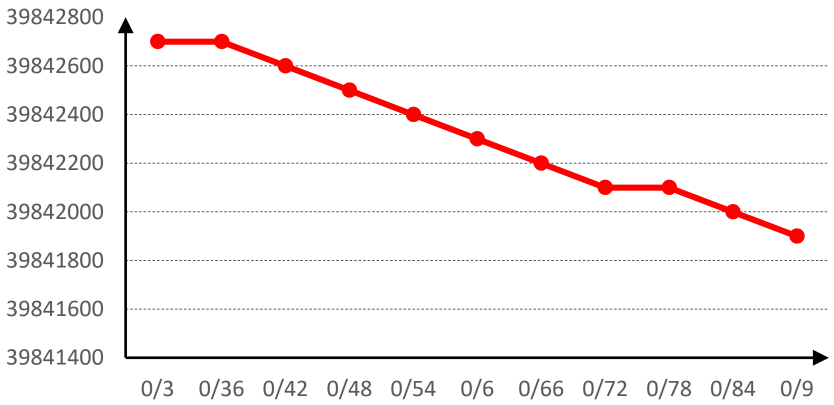

Figure 5. Trend of C^{tax} values against to OF_1

Table 10. The optimal values of $\eta_{r,s,f,t,o}$, $\Lambda_{r,s,f,t,o}$, $\mathfrak{H}^{+}_{r,s,f,t,o}$, $\ell^{+}_{r,f,t}$, $\ell^{-}_{r,f,t}$ for size number 1

$\eta_{r,s,f,t,o}$(a)	o_1
t_1	18.941
t_2	44.123
t_3	33.139

$\Lambda_{r,s,f,t,o}$(b)	o_1
t_1	2
t_2	2
t_3	2

$\mathfrak{H}_{r,s,f,t,o}$(c)	o_1
t_1	0
t_2	88.245
t_3	66.278

	$\ell^{+}_{r,f,t}$(d)
t_1	0
t_2	0
t_3	0

	$\ell^{-}_{r,f,t}$(e)
t_1	88.245
t_2	88.245
t_3	88.245

- In a range of values, the sensitivity analysis conducted on the carbon tax rate shows that the carbon tax policy has a stable and reliable performance. Despite the change in this parameter from 0.3 to 0.9, the carbon emission rate remains constant, and the deviation of costs from the budget has decreased significantly. This stability in carbon emission levels indicates the efficiency of this tool in controlling environmental effects without the need for precise parameter adjustments.
- The modeling findings show that changing the key parameters did not lead to changes in the values of the two OFs, including Penalty (Penalty = 11.544), Quality (Quality = 178.009), and Carbon Emission (Carbon Emission = 1429.913). This performance stability indicates the stability of the system under structural changes and can serve as a basis for management decisions. Therefore, strategic decisions and operational planning are necessary for management decisions to increase the efficiency of the analyses without compromising penalty, quality or environmental sustainability. On the other hand, when analytical or computational resources are limited, temporarily eliminating these three OFs leads to simplification of the current problem. This stability also becomes a management strength that can provide stability of quality and control of penalties regardless of changing conditions, instilling more confidence in the implementation and execution of the systems.

The results of this study can offer practical guidance for construction project managers and policymakers in the field of SCS management. Firstly, since transportation costs make up the largest share of total costs in all SC levels, focusing on this sector can greatly impact cost control. Secondly, increasing the ROR on investment results in higher deviation from the budget, so it is advisable to use a lower ROR in projects with financial constraints. Thirdly, extending the project implementation time horizon helps decrease deviation from the budget and enables better resource management. Fourthly, despite changes in the C^{Tax} parameter, the carbon tax policy maintains sustainable performance in terms of carbon emissions. Fifthly, the stability of the second and third OFs (penalty and quality) against parameter changes suggests that in some real-life applications, these dimensions can be simplified to streamline the decision-making process. Finally, as C^{tax} increases, costs decrease but computational time fluctuates, necessitating consideration of the trade-off between cost and time in decision-making model design. These findings can be generally applied in designing environmental policies, adjusting project parameters, and optimizing operations in real projects.

7. Discussion

Given the importance of inventory control in reducing SC costs, it is essential to focus on and prioritize this issue. However, a review of the existing literature shows that most research has primarily focused on estimating construction costs [41] and improving cost, time, and quality components. There has been less attention given to inventory control strategies, which play a crucial role in cost management. Therefore, adopting a comprehensive approach that includes CSC design, inventory control strategies, and resource delivery policies is particularly important. On the other hand, when designing an efficient SC, paying attention to environmental considerations such as greenhouse gas (carbon) emissions can bring the model closer to real-world realities. Additionally, considering the Time Value of Money due to the difference in the value of money in the present and future is considered one of the key factors in economic analysis.

In the following, the important findings of the current issue will be discussed.

- For each CSC size, total transportation costs showed significant stability. This system is very similar to the SSMD inventory production system, as shown in the study by Sarkar et al [42]. These interpretations suggest that the present study could be applied effectively in the construction chain, where costs play a significant role.
- The increase in transportation costs is a direct result of the expansion of the problem dimensions, ultimately leading to an increase in the costs of the entire system, as the findings show. It is clear that as the purchase of resources increases, transportation costs also increase. This is a result of the growth of problem dimensions and the choice of SSMD strategy. In the SSMD strategy, as explained in the paper by Sadeghi et al [10], transportation costs increase due to a higher number of deliveries compared to SSSD. Therefore, it can be concluded that the results of Sadeghi et al are consistent with the results of this study. However, this study also investigated another OF in addition to the cost objective, which was not explored in Sadeghi et al.'s [10] study.
- An increase in the number of resources leads to a significant increase in network costs, as observed in Golpîra's [21] study. However, the present study, which considers the SSMD strategy and takes into account the time value of money, was able to conduct a more comprehensive analysis of costs by including the influential parameter of inflation.
- Abdolazimi et al [7] presented the development of a sustainable future SC configuration for the construction industry. While sustainability criteria were considered, the time value of money was not factored into the SC design calculations. This study also addressed this issue.
- On the other hand, this study offers a different and complementary perspective compared to other studies. Unlike the study of Rostami et al [14]., whose main focus was on maximizing NPV using scheduling policies under uncertainty, the present study examines NPV in the context of the CSC using the SSMD strategy. While Rostami et al [14] examined the effect of scheduling on project cash flows, this study focuses on the impact of inventory control strategies and SC structure on total cost and NPV, taking into account the time value of money.
- Also, compared to the study by Hussain et al [35]., which used meta-heuristic algorithms to simultaneously optimize NPV and reduce greenhouse gas emissions, the present study provides a complementary and more detailed perspective by providing a mathematical model and detailed analysis of the effects of the carbon

tax and the time value of money. In contrast to the purely algorithm-based approach of the [35] study, in this study, inventory control policies, resource delivery strategies, and environmental considerations are examined in an integrated manner in the SC design. This comparison shows that the present model can be used as a multidimensional decision-making framework for sustainable construction projects, taking into account economic and environmental realities.

Furthermore, the findings of this study have important managerial implications:

First, the selection of an appropriate inventory control strategy (such as SSMD versus SSSD) can have a direct impact on the overall system costs. Therefore, SC managers should choose the optimal strategy based on the project characteristics, resource size, and delivery frequency. Second, considering the time value of money, especially in long-term projects, helps to make more realistic financial decisions. Third, considering environmental considerations such as carbon emissions and related policies allows decision-makers to consider the organization's social and environmental responsibility in addition to economic efficiency. Finally, the results of this research can help policymakers formulate tax incentive policies and emission-restricting regulations to develop sustainable supply chains (SSC). However, the practical implementation of the proposed model is fraught with challenges. One of the main challenges is market uncertainties and fluctuations, including changes in resource prices, inflation rates, and transportation costs, which can reduce the accuracy of the model. Also, limited access to accurate and up-to-date data, especially in projects under development, is a serious obstacle to the practical implementation of the model. Problems such as lack of coordination among different SC actors and resistance to changing existing policies also need to be addressed. In addition, the implementation of policies such as carbon taxes or cap-and-trade systems requires appropriate legal and regulatory infrastructure, which is not available in all countries. Despite the effectiveness of the proposed model in addressing sustainability dimensions in the chain design presented in this study, greenhouse gas emissions, depletion of natural resources, soil and groundwater contamination, local or regional climate changes, and effects resulting from the end of the useful life of the structure should still be given special attention as long-term environmental impacts for a comprehensive design of the SC.

Other future development directions for the model include the following:

- Although this study examined the SSMD Strategy, examining other SC strategies such as agile SC could provide a better view of the effectiveness of the model in different scenarios.
- Using complementary policies such as cap-and-trade alongside carbon taxes, and employing green technologies such as electric vehicles, renewable energy, and increased energy efficiency, can lead to a more realistic and sustainable model.
- Increasing the accuracy of the model by considering uncertainties through fuzzy or stochastic methods, especially in parameters such as demand, delivery time, and costs, is essential in future studies.
- Also, given the increasing complexity of SC design, the use of modern optimization methods such as genetic algorithms, particle swarm optimization (PSO), imperialist competition algorithms (ICA), and artificial bee algorithms (ABC), as well as the use of machine learning and reinforcement methods in dynamic and uncertain environments, presents new research horizons for researchers.
- When examining cost control and selecting the best strategy for a more comprehensive cost analysis, it is necessary to compare SSMD and SSSD strategies.
- To gain a better understanding of the network design problem, it is essential to incorporate sustainability factors, such as carbon dioxide emissions from vehicles, into the model.
- In this study, the Carbon Tax policy was examined. However, it is also necessary to consider other strategies for managing carbon emissions, such as the Carbon Cap and the Carbon Cap-and-Trade policies.

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