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Original Article

Production to Final Casting: Optimizing Environmental-Cost-Time Decisions for Ready-Mix Concrete in Construction Projects

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Abstract - *Concrete is an essential material for most construction projects. It represents a significant portion of the construction cost and time for a wide range of projects, affecting a variety of parameters, including the environmental impact of the construction project. At present, the environmental impact of CO_2 emissions can be considered one of the main reasons for the adoption of sustainable practices by the construction sector. Therefore, as almost every construction project requires large quantities of concrete, CO_2 emissions, measured in cubic meters, become significant when making cost-time decisions for a project. This study presents a conceptual framework to estimate environmental, cost, and time impacts of ready-mix concrete works from production to final casting in construction projects, using an optimization formula that can be used to support optimum decision-making for a range of different suppliers. The Active-Set Optimization Algorithm approach is designed using multi-objective formulations to boost the performance of optimum solutions across three objectives. The study presented an effective computational model with a robust decision support algorithm to enhance the sustainability, cost, and time performance of construction projects, which can help construction participants and stakeholders to efficiently adopt mitigation strategies and formulate appropriate decisions under different construction circumstances. Also, the outcomes showed that the main environmental impact associated with concrete supply is the transportation distance, and this requires specific attention to be effectively mitigated.*

Keywords - *Ready-mix concrete, Conceptual framework, Environmental-cost-time impact, Impact estimation, Trade-off optimization.*

1. Introduction

The construction industry is one of the largest consumers of resources. Concrete work is widely used in construction projects, both on-site and off-site. It is used for a variety of constructions, including buildings, bridges, overpasses, tunnels, canals, and culverts. Often, concrete is cast in place into formwork designed around spaces and dimensions specific to the project. Concrete is the most commonly used composite material by the construction industry, which has a direct effect on project cost and quality as well as environmental impact. Therefore, the environmental impact of concrete needs to be assessed in parallel with its other important characteristics, such as mechanical and chemical properties, safety, durability, and serviceability [1]. Silva et al. [2] suggested mitigating the overall impact of the construction industry by adopting a principle of environmental performance that formed the basis for supplier selection. Any environmental impact assessment of the concrete used in a construction project must consider the whole process, from the extraction of the raw materials for the concrete to the final casting. By considering the whole life cycle of the concrete, the best decisions can be made to mitigate its impact.

The built environment sector, as with other sectors globally, has adopted various short-term and long-term plans to mitigate its environmental impact. This sector is estimated to be responsible for 37% of global carbon emissions related to energy consumption, with 6% of this resulting from the building construction industry's use of concrete, aluminum, and steel [3]. Moreover, the construction sector in the Middle East alone produced about 8.7% of global CO_2 emissions, with the population of the area accounting for 6% of the world's population [4]. According to data from 2013, total GHG emissions for Iraq were 0.6% of the total global GHG emissions. The Iraqi manufacturing and construction sector accounted for 5.4% of all Iraqi GHG emissions [5]. Concrete production represents around 8% of overall global CO_2 emissions [6], with 5% of all world CO_2 emissions coming from cement manufacturing [7-9]. Further, approximately 0.5% of cement produced is used for Ready-Mix Concrete (RMC) [10]. CO_2 emissions from concrete production are expected to increase as the global population increases, requiring expansion of cities and their infrastructure. Therefore, applying the defined sustainability pillars (economic, environmental, and social) to concrete production shows that its environmental effect is the most important of these [11].

In order to mitigate emissions from the construction sector, different processes have been adopted. For instance, some European countries provide rewards for companies and contractors that meet greenhouse gas emission mitigation requirements. The Swedish Transport Administration refunds contractors up to 1% of the total project contract value for each metric ton of CO_2 emissions below a maximum limit allowed for a project [12]. In the Netherlands, a CO_2 performance ladder tool has been developed to award a bonus related to contract value based on the emissions level in a project [13]. In America, the proposed “Buy Clean California Act” awards discounts for concrete works that mitigate their global warming potential by at least 10% of the average contract of relevant projects [13]. Also, the state of New Jersey operates a similar scheme that offers incentives to contractors in the form of “tax credits” [13]. In December 2021, the United Nations reported that Iraq had signed up to the Paris Agreement of 2015. This voluntary code requires that Iraq adopt a strategy to mitigate its GHG emissions. As an initial plan for 2022–2030, the Iraqi government has said it will reduce carbon emissions by about 37 metric tons per year, with an extended action plan that can be updated to meet a mitigation goal of 1–2% of the emissions from the baseline year [14]. Although the aforementioned ambitious measures and regulations have been adopted to achieve satisfactory results in mitigating the environmental impact of concrete, they still suffer from multiple limitations, such as decision-making uncertainty, time-consuming processes, and emission quantification issues. Thus, it is necessary to develop a comprehensive framework to support the decision-making process of stakeholders in the construction sector, especially for estimating and optimizing the impacts of ready-mix concrete for construction projects.

Several recent studies have used various approaches to model the cost, time, and CO_2 emissions of concrete processes for different stages of construction projects. However, there is still a significant gap in the approaches taken to consider specific processes and activities within the upstream stage of a Life Cycle Assessment (LCA) of a concrete product. Thus, it is necessary to develop a tool that can aid decision-makers involved with sustainable concrete production to make compromises between cost and environmental impact [15]. The absence of such a tool hinders decision support for robust planning, evaluation, and selection of optimal alternatives, which may contribute to the limited operational data existing to evaluate these processes. In response to this gap, this study proposes a framework for systematic assessment and optimization that will give planners, construction managers, and decision-makers a powerful tool to optimize trade-offs between cost, time, and environmental impacts of their concrete works, by using the production-to-casting data within LCA stages for production, transportation, and casting concrete products. Therefore, construction managers can identify the optimal choice to mitigate final costs, time, and environmental impacts relating to concrete works.

2. Research Background

Increasingly, the construction industry has made strides in improving its understanding of adopting sustainable practices [16]. Sustainability, when relating to concrete, means the optimization of material and technology to enhance various target characteristics such as mechanical, economic, and environmental performance [17]. As a method to ensure the sustainability of any product, it is essential to consider environmental performance across all phases of its life cycle, something that typically has an impact on cost [18, 19]. Use of innovative materials and modern technology can help in producing a sustainable product that has, primarily, a low environmental impact. However, practically, there are legal standards for concrete products, meaning some of these alternatives cannot be used, forcing stakeholders to explore other practical options [15]. Therefore, producing sustainable concrete with a specified strength that can meet GHG emission goals is not easy in terms of production cost [20], meaning stakeholders and concrete producers have had to find solutions and alternative options to produce sustainable concrete with an optimum cost per unit. Guinée et al. [21] stated that the sustainable performance of any product’s overall life cycle can be driven by integration Between Life Cycle Assessment (LCA) and optimization techniques, which can help reduce both the cost and the environmental impact. A holistic analytical approach to LCA is important for the analysis and quantification of various impacts from producing concrete products [22]. These impacts are different for each stage of LCA and can be influenced by factors such as the choice of concrete supplier [2]. Consequently, overall cost impacts related to concrete production can be reduced through careful planning and selection of operations and activities at the upstream stages of the concrete life cycle, such as construction material selection or concrete mixture design [15]. Moreover, environmental impacts must be considered by project stakeholders for each operation throughout the entire life cycle of a construction project [23].

Reviewing research related to the life cycle of RMC production and delivery showed that there have been a number of studies that can be divided into two groups. One group examined issues related to Life Cycle Cost Assessment (LCCA), focusing on analysis, estimating, and identifying a range of parameters that influence a concrete product across its whole life or at a specific stage of its life cycle, such as trade-offs between cost and time related to concrete production, delivery, and concrete plant location. The goal was to use simulation or optimization methods to reduce cost and/or time. In this context, using a discrete event simulation for solving raw construction material delivery problems [24], a dynamic simulation system was developed to optimize trade-offs between time and cost for mixer trucks based on dispatch interval and waiting time to cast concrete in situ [25]. The Bee Colony Optimization algorithm has been used to minimize the total waiting time of concrete mixer trucks at construction sites [26]. Integration of discrete event simulation and optimization by using genetic algorithms has produced optimal decisions for the production and delivery of concrete to construction sites based on a daily routine [27]. A three-layer chromosome genetic algorithm was used to identify priorities when optimizing concrete production for plant operations and mixer truck deliveries while also considering impacts from the construction site [28]. The research presented in [29] solved an optimization transportation problem to assign suitable concrete plant mixers to minimize RMC transportation costs to the construction site. Khartabil et al. [30] examined the simultaneous supply of RMC from different plants to two casting concrete sites to achieve the optimum concrete operation cost for a construction project. Sarkar et al. [31] studied a heuristic approach coupled with a mixed integer programming method using the MATLAB program environment interface as a coding model to optimize the concrete delivery to allocated construction sites within built-up areas of a town. Pham et al. [32] used a combination of the Grey Wolf Optimizer (GWO) and the Dragonfly Algorithm (DA) to produce optimized operation of several independent batch plants to deliver RMC to different casting concrete sites. However, calculating an optimal trade-off between cost and time is no longer sufficient to meet sustainability requirements in the construction sector, and it is now cost, time, and environmental impacts that need to be the focus to move towards a sustainable construction industry, particularly when related to concrete production.

The other group examined the LCA of concrete products to assess various ecological impacts, such as greenhouse gas emissions, mainly examining emissions from different stages of the concrete life cycle to quantify carbon emissions from the upstream to downstream phases for all off-site and on-site operations of a construction project. In this vein, Kim et al. [33] studied an LCA system based on ISO standards adopted by Korea to assess environmental impact using input data and information about the concrete, delivery distance, and energy used by the batching plant. Kim et al. [34] used LCA as a method to develop a tool to aid practitioners in the construction sector in determining GHG emissions for the whole life cycle of concrete products used in construction projects. A life cycle assessment, based on the cradle-to-gate concept, was used to quantify environmental impact categories for RMC in Spain [35]. Hottle et al. [36] developed a model, based on the cradle-to-gate concept, to quantify GHG emissions from RMC in the United States. Vázquez-Calle et al. [37] applied the gate-to-gate concept within an LCA method to concrete production processes to assess CO_2 emissions from one cubic meter of RMC produced in Ecuador. Yeşilyurt et al. [38] quantified the GHG emissions of an RMC batching plant and suggested methods of mitigating carbon emissions in Turkey. Biswas et al. [39] used LCA to identify the environmental impact of one cubic meter of RMC in Qatar, and its associated impact on a final concrete product. Despite the importance of the aforementioned literature, there is a gap between prediction tools and decision-making models, resulting in a loss of practical utility for these engineering applications. So this research provides an integrated tool that ensures effective multi-impact assessment and interpretable results to improve decision-making.

The global demand for concrete has more than doubled between 1995 and 2020 [40]. Mitigating the environmental impacts of this is critical, so developing robust methods of LCA to optimize production techniques and reduce emissions by the construction industry is crucial. The previously mentioned studies were carried out on specific stages or processes within the whole life cycle of concrete production [41]. Despite the improvement in computing power, there are still few studies calculating the environmental impacts of the lifecycle as a whole [42]. Therefore, our study developed a conceptual framework that integrates assessment procedures and optimization techniques for cost and time with the associated CO_2 emissions of concrete works operations from production to final casting. This framework can potentially reduce environmental costs by examining alternative sources for concrete production and identifying the critical factors driving the related environmental impacts. The novelty of this research lies not only in proposing a comprehensive framework, but also in the integrative prediction of multiple effects of RMC, which combines with integrated optimization techniques to enhance the decision-making process of RMC from production to the final casting gate.

3. Conceptual Framework for Assessing and Optimizing the Environmental, Cost, and Time Trade-Offs of Concrete Works

The proposed conceptual environmental-cost-time framework for assessing and optimizing the cast-in-place RMC operations performance of construction projects starts by estimating production impacts from each concrete batching plant. Then, it lists alternative options available to supply the required concrete to each construction site. Third, it estimates the concrete transportation costs and delivery time, based on the machinery used, with the environmental impacts for each alternative option. Fourth, it estimates the concrete casting impacts based on the machinery used. Fifth, it uses optimization techniques to compare the final outputs for the proposed alternatives to calculate the optimum environmental-cost-time for casting concrete in situ. Specifically, after a statistical analysis of data from concrete batching plants and construction projects, the time, cost, and environmental impacts for the concrete casting required are optimized, based on estimating materials and machine use by using an intelligent algorithm. The available environmental-cost-time data, accounting for the process from production to final casting within the LCA of construction products, allows all concrete casting operations to be broken down into three main operation stages across the five stages of LCA of upstream concrete production, as shown in Figure 1.

The cost of concrete is determined using the unit prices specified by the concrete suppliers and construction companies for each batching plant, and the time based on their design capacities. The environmental impact of the concrete production is determined by multiplying the equivalent value of CO_2 emissions for the estimated quantity of fossil fuel or energy used by the production machinery and equipment. Further, concrete transportation impact estimates are based on traveling distances and machinery used; casting impact estimates are based on the capacities of machinery used and their characteristics. This environmental-cost-time breakdown can be used for the estimation of the impact of the concrete casting for different construction activities and concrete structural elements, once machinery characteristics, transportation distances, construction sites characteristics, and concrete quantities and characteristics have been estimated.

The described environmental-cost-time framework estimates direct values of environmental cost per cubic meter based on optimum options available at different steps of the concrete production and casting, as these values are typically heavily influenced by factors such as the type of concrete batching plant, the properties of concrete required, transportation machinery, and equipment to be used. Thus, considering all these factors to estimate different impacts increases the potential for the model to be used and increases its level of generalization. It can then support decision-makers to make optimum choices, substantially mitigating the effects of final concrete casting in construction projects.

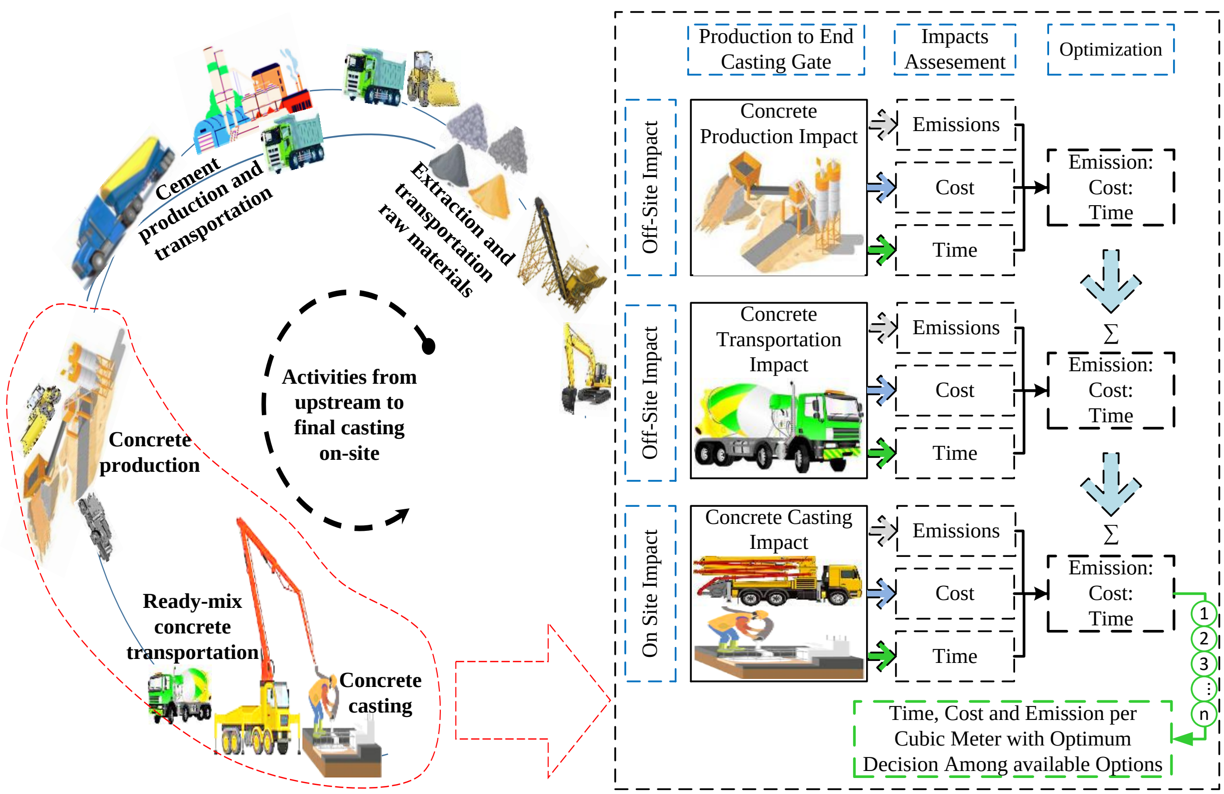

Fig. 1 A framework for optimizing key impacts based on the activities included in the upstream LCA for concrete production

3.1. Equations for Quantifying Different Impacts

The proposed framework uses the following Equations (1)-(12) to estimate all environmental, cost, and time impacts across the whole process from concrete production to final casting.

$$T_T = \sum_1^i (T_{cp} + T_{ct} + T_{cc}) \quad (1)$$

$$C_T = \sum_1^j (C_{cp} + C_{ct} + C_{cc}) \quad (2)$$

$$E_T = \sum_1^k (E_{cp} + E_{ct} + E_{cc}) \quad (3)$$

$$T_{cp} = \frac{Volume\ of\ mixer\ (m^3)}{Capacity\ of\ batching\ plant\ (m^3/hour)} \times 60 \quad (4)$$

$$T_{ct} = \frac{Distance\ from\ plant\ to\ site\ (km)}{Average\ speed\ of\ truck\ mixer\ (km/hour)} \times 60 \quad (5)$$

$$T_{cc} = \frac{Volume\ of\ concrete\ casting\ \ (m^3)}{Discharge\ of\ concrete\ pump\ (m^3/min)} \quad (6)$$

$$C_{cp} = \frac{Total\ operational\ cost\ of\ batching\ plant\ \ (USD/hour)}{Productivity\ of\ batching\ plant\ (m^3/hour)} \quad (7)$$

$$C_{ct} = \frac{Total\ operational\ cost\ of\ truck\ mixer\ \ (USD/hour)}{Productivity\ of\ truck\ mixer\ (m^3/hour)} \quad (8)$$

$$C_{cc} = \frac{Total\ operational\ cost\ of\ concrete\ pump(USD/hour)}{Productivity\ of concrete\ pump\ (m^3/hour)} \quad (9)$$

$$E_{cp} = \frac{Total\ fossil\ fuel\ or\ energy\ consumed\ of\ plant\ \left(liter\ or \frac{MJ}{hour}\right) \times equivilent\ factor\ of\ CO_2\ emissions\ (kg\ CO_2/liter\ or\ MJ)}{Productivity\ of\ batching\ plant\ (m^3/hour)} \quad (10)$$

$$E_{ct} = \frac{Total\ fossil\ fuel\ consumed\ of\ truck\ mixer\ \left(\frac{liter}{hour}\right) \times equivilent\ factor\ of\ CO_2\ emissions\ (kg\ CO_2/\ liter)}{Productivity\ of\ truck\ mixer\ (m^3/hour)} \quad (11)$$

$$E_{cc} = \frac{Total\ fossil\ fuel\ consumed\ of\ concrete\ pump\ \left(\frac{liter}{hour}\right) \times equivilent\ factor\ of\ CO_2\ emissions\ (kg\ CO_2/\ liter)}{Productivity\ of concrete\ pump\ (m^3/hour)} \quad (12)$$

Where T_T is the total time for each cubic meter of concrete from production to final casting (min/m^3). T_{cp} is the production time for each cubic meter of concrete in the batching plant. T_{CT} is the transportation time for each cubic meter of concrete from the plant to on-site casting. T_{cc} is the casting time for each cubic meter of concrete cast. C_T is the total cost for each cubic meter of concrete from production to final casting (USD/m^3). C_{CT} is the transportation cost for each cubic meter of concrete from the plant to on-site casting. C_{cc} is the Casting cost for each cubic meter of concrete cast. E_T is the total CO_2 emissions for each cubic meter of concrete from production to final casting (kg CO_2/m^3). E_{CP} is the production of CO_2 emissions for each cubic meter of concrete in the batching plant. E_{ct} is the transportation CO_2 emissions for each cubic meter of concrete from the plant to on-site casting. E_{cc} is the casting CO_2 emissions for each cubic meter of concrete cast.

3.2. Using the Active-Set Optimization Algorithm

The Active-Set Method is an optimization technique used to solve constrained optimization problems, particularly those involving both equality and inequality constraints. This method works by iteratively identifying and updating a subset of constraints, referred to as the active set, which are binding, or close to being binding, at the solution. The method focuses on solving a reduced problem involving only these active constraints, making it computationally efficient for large-scale problems. The Active-Set Method is fundamental to optimization strategies such as Sequential Quadratic Programming (SQP), and is strongly related to the Karush-Kuhn-Tucker (KKT) conditions, which describe necessary conditions for a solution to be optimal in constrained scenarios [43, 44]. The Active-Set Method's theoretical foundations are built on the concept of an active set, which is the subset of constraints that are either binding (satisfied as equalities) or nearly binding at the current iteration of the optimization process. The method operates by iteratively refining this active set, focusing computational efforts on these constraints while ignoring inactive ones. This approach allows the algorithm to reduce the problem's dimensionality at each step, making it more efficient than methods that simultaneously consider all constraints. The general constrained optimization problem that the Active-Set Method addresses can be formulated as shown in Equations (13)-(15) [43, 44]:

$$\min_{x \in \mathbb{R}^n} f\ (x) \quad (13)$$

Subject to:

$$g_i\ (x) \leq 0, i = 1, \dots, m \quad (14)$$

$$h_j\ (x) \leq 0, j = 1, \dots, p \quad (15)$$

Where $f(x)$ is the objective function to be minimized, $g_i(x)$ represents the inequality constraints, $h_j(x)$ represents the equality constraints, and (x) is the vector of decision variables.

The Active-Set Method is particularly effective in Quadratic Programming (QP), where the objective function is quadratic, and the constraints are linear. It is widely used in portfolio optimization, where the goal is to maximize returns while minimizing risk, subject to constraints such as budget limitations and regulatory requirements. In engineering, it is used in structural optimization to design structures that minimize weight or cost while satisfying stress and displacement constraints [45]. Another significant application of the Active-Set Method is in Sequential Quadratic Programming (SQP), a powerful technique for solving nonlinear optimization problems. In SQP, the nonlinear problem is approximated by a series of quadratic subproblems, each of which is efficiently solved using the Active-Set Method. This approach is common in control systems, robotics, and aerospace engineering, where nonlinear dynamics and constraints are prevalent [43].

Within the framework developed for this study, an Active-Set optimization model is used to find the optimal concrete supply for construction projects based on the concrete requirements of each project and the plant capacity. The design of this quantitative system aims to minimize carbon emissions (Kg/m^3), cost per cubic meter of concrete (USD/m^3), and delivery time from the plant to the project site (min), without affecting the project's concrete requirements. Therefore, the model developed to meet the most environmental requirements within the budget allocated for each item, based on the planned management strategy, is shown in Figure 2. The complete Active-Set Global Search algorithm procedure is coded in MATLAB and then used to find optimal solutions for the available options. Equations (16)-(18) show the mathematical model's objective functions and constraints. Figure 3 shows the steps for this model's optimal solution mechanism for the Active-Set Global Search algorithm using MATLAB scripts.

$$Minimize: [x, E, C, T, WE, WC, WT] \quad (16)$$

Subject to:

$$\sum A + B + C + D + E + F + H + I + J = D_P \quad (17)$$

$$\sum \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6 + \beta_7 + \beta_8 + \beta_9 \leq C_{PA} \quad (18)$$

Where x is the number of trucks leaving each station for each project. *E* is the normalized carbon emissions (kg CO_2/m^3). *C* is the normalized cost of the cubic meter of concrete (USD/m^3). *T* is the normalized time from sites to plants (min). WE, WC, and WT are weighting factors for emissions, cost, and time, respectively. *A*, *B*, *C*, *D*, *E*, *F*, *H*, *I*, *J* are the sum of demand from all batching plants for each site. $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9$ are the sum of capacity for each batching plant. D_P is the requirements of each project for concrete (m^3). C_{PA} is the concrete capacity of mixer trucks (m^3).

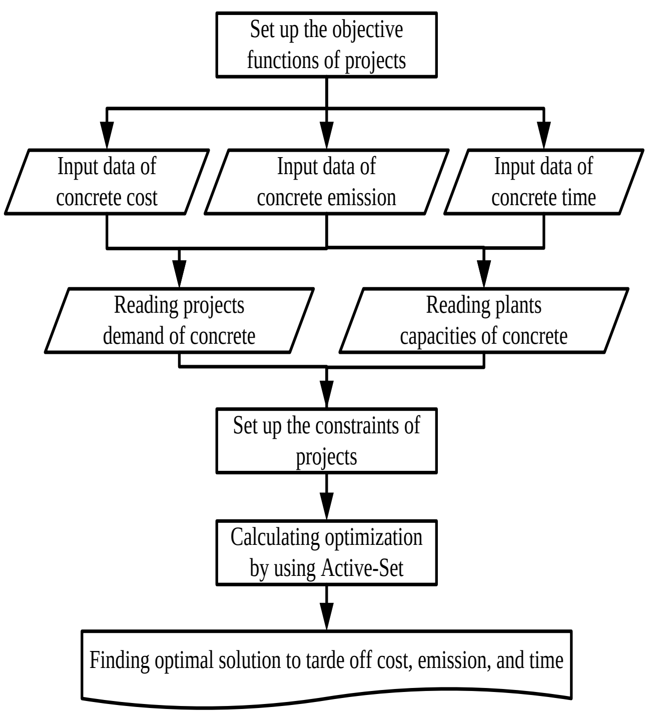

Fig. 2 The flowchart of the development optimization model

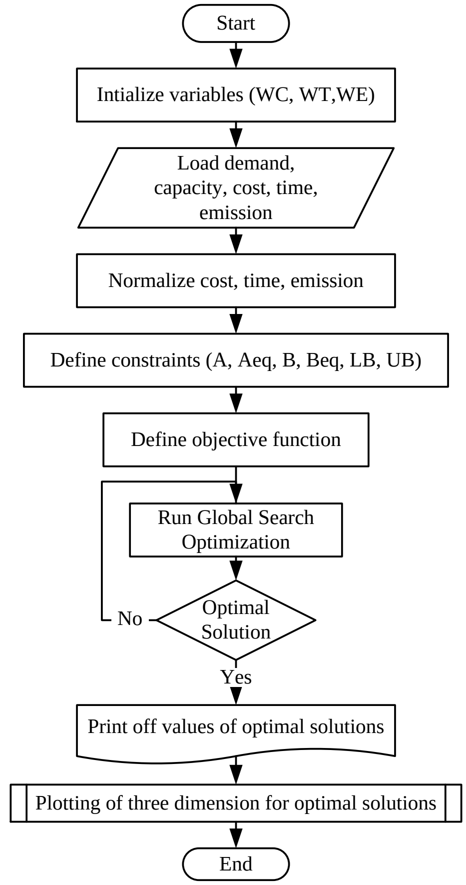

Fig. 3 The active-set mechanism for the optimal solution

3.3. Case Study to Implement the Proposed Framework

To test and verify that the developed framework assesses impacts and optimizes the decision-making process for concrete supply and casting, a case study analysis was carried out by considering the impacts of concrete production on final in situ casting. The case study involved a number of concrete batching plants and construction projects that needed to pour their raft foundations.

Construction managers were able to use a number of concrete batching plants (A, B, C, D, E, F, G, H, I, and J) to pour foundations for different projects (I, II, III, IV, V, VI, VII, VIII, and IX), considering requirements from zero to the maximum plant capacity, to optimize overall cost, time and CO_2 emissions per cubic meter of concrete produced. Cost, time, and emission estimates used general, developed, and/or simplified formulas to predict near-actual values, as described in the section above. The framework involved formally assessing and considering all activities within the specified stages of LCA for a concrete product. Further, the case study locations of the concrete batching plants and construction sites were located in different places in Hilla city, Babylon, Iraq. The data were collected, and all activities for the selected case studies were documented based on inventory sheets.

In the selected case studies, the optimization technique was applied to concrete supply during foundation pouring works at nine construction sites (projects I, II, III, IV, V, VI, VII, VIII, and IX), which were supplied RMC (C35) from ten concrete batching plants (plants A, B, C, D, E, F, G, H, I, and J). Their production rates were, respectively, 75, 48, 60, 50, 65, 90, 70, 40, 35, and 80 (m^3/h). Each site required a different volume of concrete for its pouring works at the same time. In addition, the concrete requirement for each construction site (I-IX) was 250 m^3, 300 m^3, 100 m^3, 170 m^3, 90 m^3, 595 m^3, 700 m^3, 315 m^3, and 475 m^3, respectively. The individual distances between batching plants and construction sites are shown in Table 1. Table 2 shows the characteristics of the machines available for transporting and pouring concrete for each of the projects.

Table 1. Batch plants' capacities, distances, and concrete requirements for each project

		Distance between sites and plants (km)								
Batch Plant	**Capacities (m^3/h)**	**Project I**	**Project II**	**Project III**	**Project IV**	**Project V**	**Project VI**	**Project VII**	**Project VIII**	**Project IX**
A	75	16	14	20	24	18	13	19	22	26
B	48	28	18	22	16	14	24	26	18	30
C	60	15	40	34	22	26	32	17	24	14
D	50	18	26	17	32	20	22	30	28	36
E	65	22	15	18	20	30	26	34	13	24
F	90	14	10	21	26	22	15	21	22	30
G	70	26	16	24	18	16	28	26	20	30
H	40	12	32	34	24	30	22	20	28	18
I	35	18	28	18.4	36.6	18	26	32	26	34
J	80	22	18	22	23	30	24	28	14	24
Requirements (m^3)		250	300	100	170	90	595	700	315	475

Table 2. Machinery characteristics for each project

Machinery		**Project I**	**Project II**	**Project III**	**Project IV**	**Project V**	**Project VI**	**Project VII**	**Project VIII**	**Project IX**
Pumps	**(m^3/h)**	40	50	60	25	35	30	25	30	35
	Number	1	1	1	1	1	1	1	1	1
Trucks	**(m^3)**	5	5	5	5	5	5	5	5	5
	Number	9	9	9	9	9	9	9	9	9

3.4. Data Required to Run the Development Model

The data required to run the developed framework includes concrete material quantities with their production time, cost, and emission values per measured unit, adapted for each specific batching plant and/or machine used in processing. This involves the operational cost and time of these upstream processes based on different methods and machines used to produce the concrete product. In addition, estimations of their emissions have to be made, based on equivalent energy-fuel factors for each machine or process through each step, in order to estimate the impacts of the construction process and/or concrete product. The cost of producing the concrete product is calculated based on the cost of the supplier for each factory, plus the cost of transporting the product to its final destination and casting in situ. It is assumed that all concrete batching plants have their own mixer trucks, so that they can control the quality of the concrete from production to delivery. Further, the transportation costs differ for each supplier depending on the distance between batching plants and the construction sites, which also affects the time required for delivery, taking into account the average speed of trucks between two points. Other input data required to assess various impacts in the developed framework, such as the cost of concrete production, transportation, and cast-in-place/formwork, are calculated based on the hourly rental of the concrete batching plant, mixer truck, and concrete pump per hour. All these costs depend on the capacities of machines and their usage. The framework attempts to minimize the idle time of different components within production, transportation, and casting processes by using different supply sources for different projects. For example, concrete work relied on the continuous pouring activity of nine mixer trucks from each concrete batching plant, as shown in Table 2, to meet the concrete requirement of Project I. Tables 3, 4, and 5 show different estimated impacts per cubic meter based on calculated values for each project by using the equations developed for the proposed framework.

Table 3. CO_2 emissions from concrete production to final casting for each project

CO_2 emission per cubic meter (kg/m^3)									
Batch Plant	**Project I**	**Project II**	**Project III**	**Project IV**	**Project V**	**Project VI**	**Project VII**	**Project VIII**	**Project IX**
A	56.16	49.14	70.2	84.24	63.18	45.63	66.69	77.22	91.26
B	98.28	63.18	77.22	56.16	49.14	84.24	91.26	63.18	105.3
C	52.65	140.4	119.34	77.22	91.26	112.32	59.67	84.24	49.14
D	63.18	91.26	59.67	112.32	70.2	77.22	105.3	98.28	126.36
E	77.22	52.65	63.18	70.2	105.3	91.26	119.34	45.63	84.24
F	49.14	35.1	73.71	91.26	77.22	52.65	73.71	77.22	105.3
G	91.26	56.16	84.24	63.18	56.16	98.28	91.26	70.2	105.3
H	42.12	112.32	119.34	84.24	105.3	77.22	70.2	98.28	63.18
I	63.18	98.28	64.584	128.466	63.18	91.26	112.32	91.26	119.34
J	77.22	63.18	77.22	80.73	105.3	84.24	98.28	49.14	84.24

Table 4. Concrete costs from production to final casting for each project

Cost per cubic meter (USD/m^3)									
Batch Plant	**Project I**	**Project II**	**Project III**	**Project IV**	**Project V**	**Project VI**	**Project VII**	**Project VIII**	**Project IX**
A	80	70	100	120	90	65	95	110	130
B	140	90	110	80	70	120	130	90	150
C	75	200	170	110	130	160	85	120	70
D	90	130	85	160	100	110	150	140	180
E	110	75	90	100	150	130	170	65	120
F	70	50	105	130	110	75	105	110	150
G	130	80	120	90	80	140	130	100	150
H	60	160	170	120	150	110	100	140	90
I	90	140	92	183	90	130	160	130	170
J	110	90	110	115	150	120	140	70	120

Table 5. Time consumption from concrete production to final casting for each project

Time per cubic meter (min/m^3)									
Batch Plant	**Project I**	**Project II**	**Project III**	**Project IV**	**Project V**	**Project VI**	**Project VII**	**Project VIII**	**Project IX**
A	42.7	37.3	53.3	64.0	48.0	34.7	50.7	58.7	69.3
B	67.2	43.2	52.8	38.4	33.6	57.6	62.4	43.2	72.0
C	45.0	120.0	102.0	66.0	78.0	96.0	51.0	72.0	42.0
D	56.8	82.1	53.7	101.1	63.2	69.5	94.7	88.4	113.7
E	58.7	40.0	48.0	53.3	80.0	69.3	90.7	34.7	64.0
F	48.0	34.3	72.0	89.1	75.4	51.4	72.0	75.4	102.9
G	104.0	64.0	96.0	72.0	64.0	112.0	104.0	80.0	120.0
H	41.1	109.7	116.6	82.3	102.9	75.4	68.6	96.0	61.7
I	54.0	84.0	55.2	109.8	54.0	78.0	96.0	78.0	102.0
J	75.4	61.7	75.4	78.9	102.9	82.3	96.0	48.0	82.3

3.5. Optimization Output based on the Developed Model

The primary objective was to determine appropriate values for cost, time, and emissions when linking different construction sites and batching plants. Since the main assumption for complete process design involves similar weighted values for time, cost, and emissions, these are applied in the optimization process to concrete suppliers, based on the breakdown structure of data aggregated from production to final casting within the concrete life cycle analysis. Tables 6 and 7 illustrate the optimization options available for concrete supplied from different batching plants for different projects where the probabilities of such occurrences when concrete is produced within the maximum capacities of the batching plants (A, B, C, D, E, F, G, and J) are given by the requirements of projects and available number of mixer trucks with capacities mentioned in Table 2. The other batching plants (H and I) have probabilities of zero percent for all projects investigated, which may provide a brief indication of the effect of plant capacity and distance in this case, which may be useful to facilitate optimal decision making.

Table 6. The quantity of concrete supplied from each batching plant has an impact

Batch Plant	Concrete supplied	Project I	Project II	Project III	Project IV	Project V	Project VI	Project VII	Project VIII	Project IX
	m^3	35	---	55	70	35	---	275	125	---
A	kg CO_2	1965.6	---	3861	5896.8	2211.3	---	18339.75	9652.5	---
	USD	2800	---	5500	8400	3150	---	26125	13750	---
	min	1494.5	---	2931.5	4480	1680	---	13942.5	7337.5	---
	m^3	---	---	45	---	---	---	---	---	---
B	kg CO_2	---	---	3474.9	---	---	---	---	---	---
	USD	---	---	4950	---	---	---	---	---	---
	min	---	---	2376	---	---	---	---	---	---
	m^3	---	---	---	30	---	70	170	---	120
	kg CO_2	---	---	---	2316.6	---	7862.4	10143.9	---	5896.8
C	USD	---	---	---	3300	---	11200	14450	---	8400
	min	---	---	---	1980	---	6720	8670	---	5040
	m^3	---	---	---	---	---	---	---	---	30
	kg CO_2	---	---	---	---	---	---	---	---	3790.8
D	USD	---	---	---	---	---	---	---	---	5400
	min	---	---	---	---	---	---	---	---	3411
	m^3	---	115	---	---	---	---	75	190	145
	kg CO_2	---	6054.75	---	---	---	---	8950.5	8669.7	12214.8
E	USD	---	8625	---	---	---	---	12750	12350	17400
	min	---	4600	---	---	---	---	6802.5	6593	9280
	m^3	165	---	---	---	55	305	---	---	15
F	kg CO_2	8108.1	---	---	---	4247.1	16058.25	---	---	1579.5
	USD	11550	---	---	---	6050	22875	---	---	2250
	min	7920	---	---	---	4147	15677	---	---	1543.5
	m^3	50	185	---	---	---	90	---	---	---
G	kg CO_2	4563	10389.6	---	---	---	8845.2	---	---	---
	USD	6500	14800	---	---	---	12600	---	---	---
	min	5200	11840	---	---	---	10080	---	---	---
H	---	---	---	---	---	---	---	---	---	---
I	---	---	---	---	---	---	---	---	---	---
	m^3	---	---	---	70	---	130	180	---	165
J	kg CO_2	---	---	---	5651.1	---	10951.2	17690.4	---	13899.6
	USD	---	---	---	8050	---	15600	25200	---	19800
	min	---	---	---	5523	---	10699	17280	---	13579.5

Table 7. Total quantity of concrete supplied from each batching plant with impacts

Index	Unit	Project I	Project II	Project III	Project IV	Project V	Project VI	Project VII	Project VIII	Project IX
Total impact	$kgCO_2$	14637	16444	7336	13865	6458	43717	55125	18322	37382
	USD	20850	23425	10450	19750	9200	62275	78525	26100	53250
	min	14615	16440	5308	11983	5827	43176	46695	13931	32854
Impact per cubic meter	$kgCO_2$	58.55	54.81	73.36	81.56	71.76	73.47	78.75	58.17	78.70
	USD	83	78	105	116	102	105	112	83	112
	min	58.5	54.8	53.1	70.5	64.7	72.6	66.7	44.2	69.2

4. Results and Discussion

The case study for this paper was based on available alternatives for concrete batching plants used to provide the concrete for nine projects at different locations in the city of Hilla. RMC has been widely used in Iraq for various construction projects, ranging from small private homes to large construction projects, to comply with the characteristics and regulations applied to the quality of concrete works in construction projects, especially relating to climate change. Iraq is dedicated to reducing the CO_2 emissions from industrial sectors, with specific climate change mitigation plans for the construction industry sector. Calculations have been developed to allow the comparison of baseline data with new scenarios that try to optimize cost, time, and reduce emissions. This study examined the use of several batching plants across several projects. For this study, RMC was produced by either relatively small or medium-sized dry batching plants, with the same mix ratio for all concrete produced, and then transported to the construction site.

As the results from this study were based on an average daytime temperature of around 37°C in the study areas during the first week of May 2025, this meant using specific concrete additives to maintain the workability and required compressive strength. The average fossil fuel usage to provide energy required for one cubic meter of RMC from production to final casting was around 20-31 liters/m^3, emitting 54-81 equivalent kg CO_2/m^3, with an average time and cost of around 44–73 min/m3 and 78–116 USD/m^3, respectively. These results are for producing and transporting concrete 10–37 km, one way from source to final destination, in addition to casting time, as shown in Table 1. The calculations and formulas used in the developed framework were based on data collected from concrete batching plant inventory and machinery databases that were compiled during machine operations. Thus, the accuracy of documented data is an important issue for the ultimate validity of the final decision made, which may be more sensitive to changes in some data. Moreover, it is also often impossible to collect certain input data due to uncertainty or poor recording in some off-site processes, in which case it is necessary to resort to their estimation based on some historical and theoretical indications. Furthermore, some assumptions were considered as limitations of the database of registered mixer trucks, related to the average usage speed and traffic conditions across the routes used between batching plants and projects. It is important to note that the operating conditions of all roads linking concrete production plants and construction sites are roughly similar in terms of traffic congestion, rush hour times, and the design of the main roads connecting with them. However, Hilla is an inland city with a limited road network connecting the interior and exterior of the governorate. Therefore, concrete batching plants are located outside the city's municipal boundaries, in rural areas. It should be highlighted that the time to transport concrete from plants to construction sites mainly depends on distances between them and the differing traffic conditions at specific times. This fact is consistent with the results of previous research that highlighted the effects of travel distances on the environmental impact of various construction projects [46].

From an optimization technology perspective, the Active-Set Method offers several advantages, as it is particularly efficient at handling large-scale problems where only a few constraints are active for the solution. This algorithm has been recognized as an effective numerical optimization technique adopted for tackling constrained regression problems [43]. The method is also flexible, capable of handling both equality and inequality constraints, and it can be adapted for various types of optimization problems, including nonlinear problems using SQP. Its simplicity and interpretability make it a popular choice for practical applications where ease of implementation and understanding are important [47].

However, the Active-Set Method has some limitations, as it is sensitive to the choice of the initial feasible solution and active set. A poor initial guess can lead to slow convergence or suboptimal solutions. The method can also become inefficient for problems where the active set changes frequently, as each change requires solving a new subproblem. Furthermore, it may suffer from numerical stability issues, particularly in ill-conditioned problems or when the solution is near the boundary of the feasible region. In dense constraint environments, where many constraints are binding simultaneously, the method can be less efficient than other techniques such as interior-point methods [43].

In this context, the results of optimization showed that the optimal supply chains for concrete casting in any construction project involved output from several batching plants. Arrangements were made to operate the batching plants with the equipment and design production capacity to cover the requirements of each project. A dash in the output data table indicates that the batching plant under consideration was not considered as a concrete supplier for a specific project. In order to validate the optimal solution of the algorithms used in practice, several concrete batching plants were evaluated for the supply of the whole volume of concrete required for each project, as shown in Figures 4-12. The results confirmed our findings as an optimal solution to mitigate the main impacts of concrete works. Optimization of the process from concrete production, through transportation to final casting, reduces CO_2 emissions by 4-47% compared to a baseline scenario calculated for each project. Most CO_2 emissions resulted from transportation, whereas concrete production and casting by pump accounted for only 4.8-9.5% of emissions. The CO_2 emissions produced by the use of small finishing tools for casting activities in these calculations were ignored. Table 7 shows the total and per cubic meter impacts based on an optimum solution for concrete CO_2 emissions, cost, and time consumption using RMC from the concrete production gate to final casting.

In nutshell, the model developed in this study is predominantly an integration of estimation formulas and three-dimensional optimization algorithms, where the results show evidence of the model effects that have engaged in both the theoretical insight for future research relating to addressed and unaddressed factors and other practical implications for practitioners and stakeholders in the construction industry to implement mitigation strategies that can facilitate the achievement of future requirements and sustainable objectives of the construction sector.

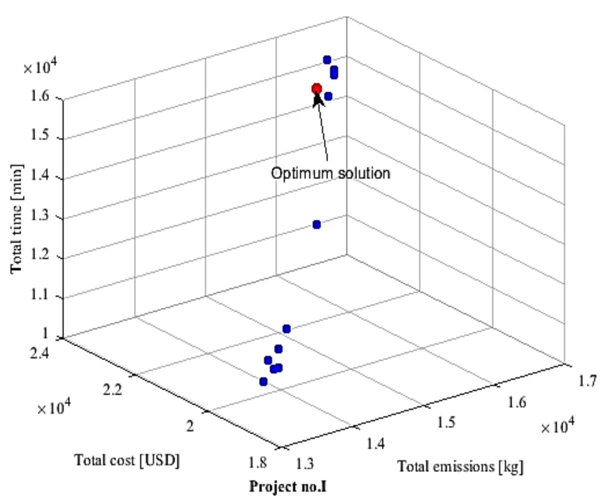

Fig. 4 The optimal solution reached by active-set for environment, cost, and time trade-offs in project I

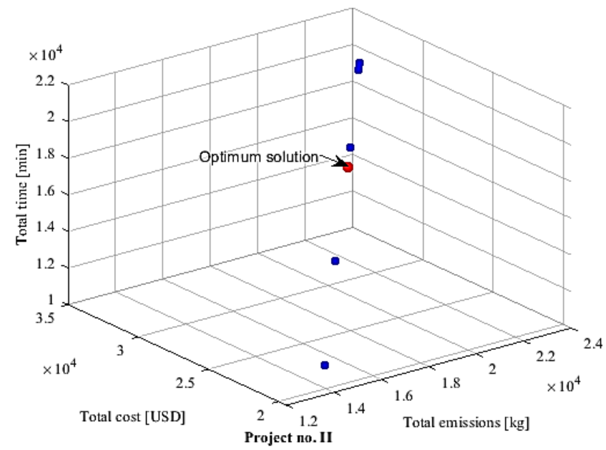

Fig. 5 The optimal solution reached by Active-Set for environment, cost, and time trade-offs in project II

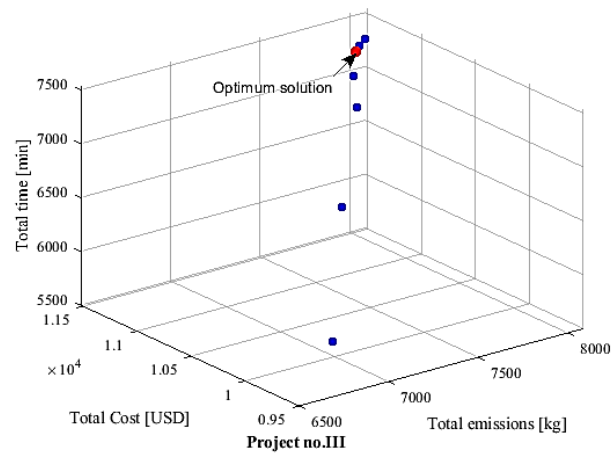

Fig. 6 The optimal solution reached by Active-Set for environment, cost, and time trade-offs in project III

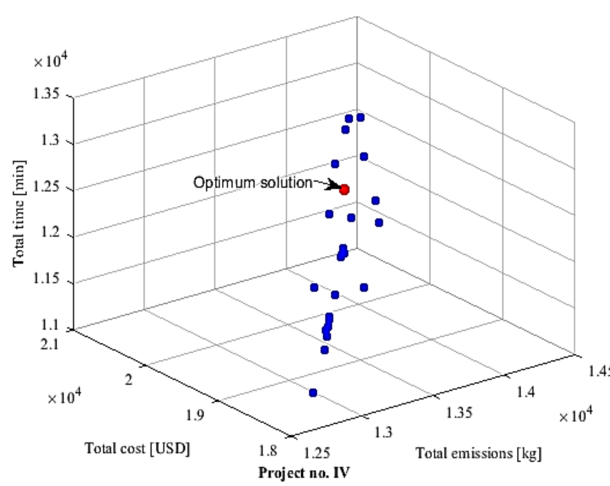

Fig. 7 The optimal solution reached by active-set for environment, cost, and time trade-offs in project IV

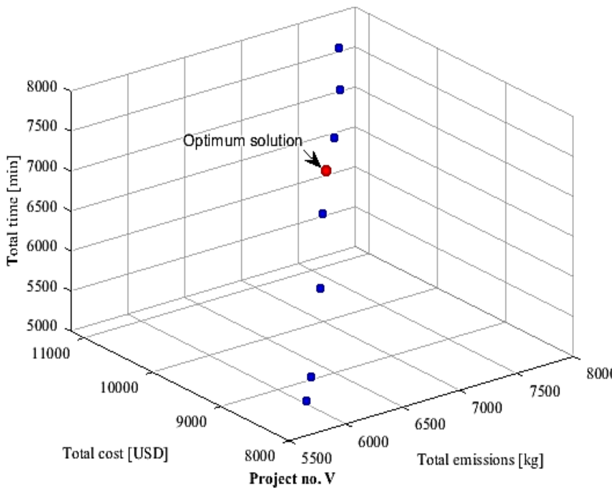

Fig. 8 The optimal solution reached by active-set for environment, cost, and time trade-offs in project V

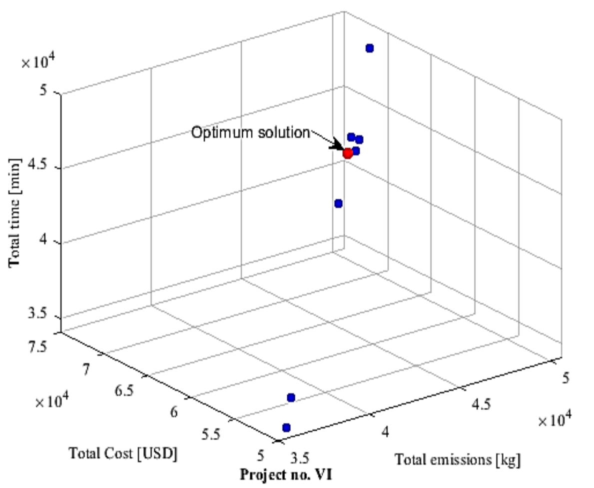

Fig. 9 The optimal solution reached by active-set for environment, cost, and time trade-offs in project VI

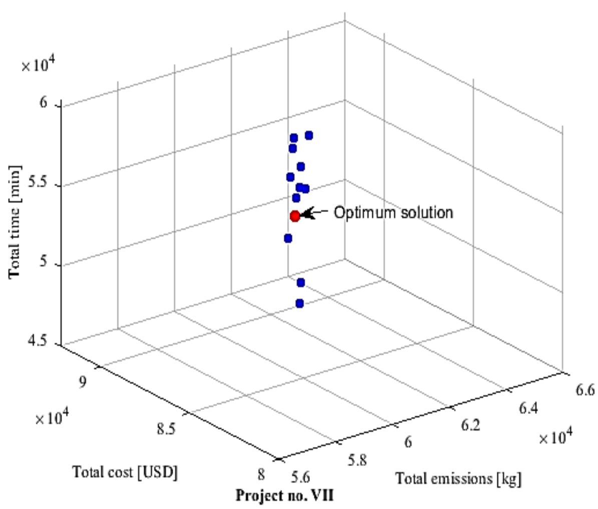

Fig. 10 The optimal solution reached by active-set for environment, cost, and time trade-offs in project VII

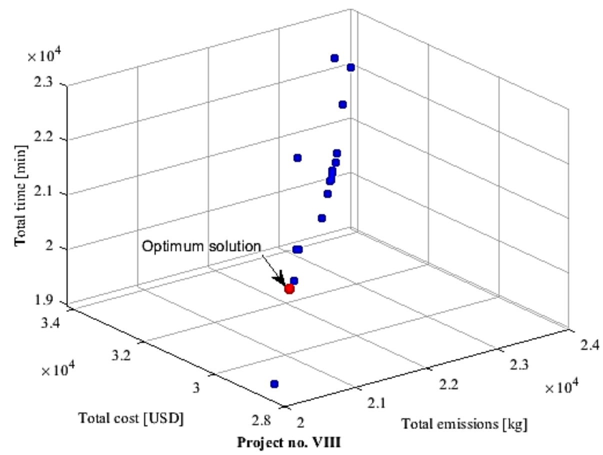

Fig. 11 The optimal solution reached by active-set for environment, cost, and time trade-offs in project VIII

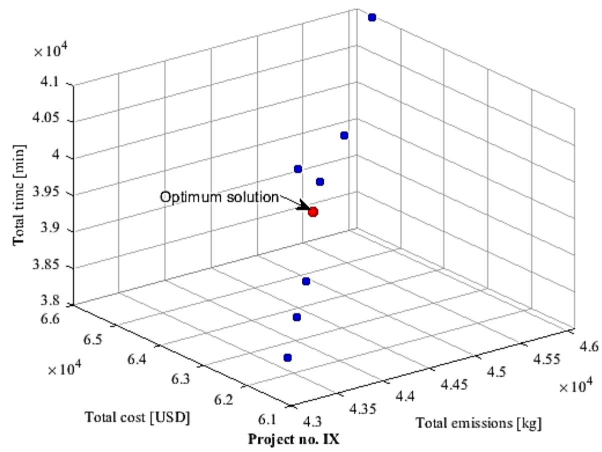

Fig. 12 The optimal solution reached by active-set for environment, cost, and time trade-offs in project IX

5. Conclusion

Despite rapid improvements in technology and machinery offered by construction equipment manufacturers, concrete producers and suppliers still need to carefully plan and consider broader potential options within the entire concrete life cycle to mitigate the impacts of concrete usage by construction projects. These options should be based on complying with sustainability regulations, whilst ensuring an appropriate cost of meeting environmental targets. Practical solutions applied to various stages of concrete usage should be used to mitigate the environmental impacts of concrete.

This study developed an integrated methodological framework with equations and algorithms designed to assess and improve the decision-making process regarding the environmental impact, cost, and time of a concrete product from production to final casting. Using this framework for construction projects to control the impact of concrete works and to develop an environmental plan for construction activities could help to mitigate global emissions for this sector. An objective of this study was to develop a model based on an Active-Set Optimization algorithm in order to minimize the trade-offs between emissions, cost, and time when using RMC on different construction sites. An optimal selection of RMC suppliers can lead to the reduction of environmental impacts and costs. The model was designed to apply to construction stakeholders.

A case study from the Iraqi industrial construction sector was used to calculate CO_2 emissions, along with cost and time indicators for ten concrete batching plants providing RMC for nine construction projects. This confirmed that the RMC transportation distances are a major factor dominating the volume of CO_2 emissions. Therefore, careful selection of available concrete suppliers is necessary to help mitigate the impacts of using RMC by the construction sector. The optimal number of batching plants to use for our case study was eight, equating to 100% efficiency based on designed capacities, along with a reduction in transportation costs, leading to a reduction in emissions per m^3 of concrete. The results of this study provide valuable insights into the different impacts of concrete works and the effectiveness of specific processes in mitigating these impacts. These insights can be used to improve the RMC efficiency of construction projects and reduce environmental impacts. However, there are still many uncertainties that exist during the construction implementation process, which may or may not arise when executing a specific task of RMC operations in construction projects, such as the difficulty of sudden traffic stop during the casting process, changing the driving mode of truck mixers during transportation activities, or increased waiting time for casting on-site due to an equipment defect, to fully reflect more impacts within the ready-mix concrete activities that can be investigated in the extended model, for example, based on a simulation dataset. In addition, future studies should focus on exploring the effects of other upstream tasks on emissions generated per unit volume of concrete, and developing a comprehensive optimization model to improve the accuracy of environmental assessments, thus enhancing decision-making for all upstream stages (cradle-to-gate).

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Author Contributions

Hassanean S. H. Jassim; conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing-original draft preparation, writing-review and editing, supervision, project administration. Musaab F. Hasan; software, validation, writing-original draft preparation. All authors have read and agreed to the published version of the manuscript.

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