

## Article

# Optimizing Concrete Grade for a Sustainable Structural Design in Saudi Arabia

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**Abstract:** Buildings and facilities undergo several stages: the product stage, the construction stage, the use stage, the end-of-life stage, and the recycling stage. The life cycle of any facility or building contributes to embodied carbon (EC) emissions. The product stage, also known as the cradle-to-gate stage (A1–A3), registers the highest emissions, estimated to account for 70% of the total environmental impact. The continuing population growth in Saudi Arabia necessitates urgent action to identify and implement solutions for reducing greenhouse gas emissions and mitigating environmental risks. This study investigates the optimal method to analyze the grade of concrete for specific structural elements (columns) in a particular work area, adhering to accurate and methodological standards outlined in the Saudi Building Code (SBC). The bill of quantities (BOQ) determined the amount of building materials for the structure considered in this study. Reliable embedded carbon coefficients (ECCs) for structural materials such as concrete and steel were determined following life cycle assessment principles. They were analyzed using the Inventory of Carbon and Energy (ICE; Version 2.0) and Global Warming Potential (GWP). The obtained values varied based on the components of each mixture. This study determined the cost of each concrete mixture and steel, selecting the optimal mixture based on both EC and material cost. Since the quantity of cement significantly affects EC emissions in a concrete mixture, it is essential to select appropriate plasticizers and concrete types. This study evaluated the C30, C40, C50, C60, and C70 mixtures. Among these, the C70 mixture demonstrated the best environmental impact and was the least expensive compared to the basic C40 mixture for the estimated quantities of concrete and steel. The estimated reductions in cost and environmental impact were 33% and 27%, respectively. This groundbreaking study paves the way for low-carbon structural design in large hotels across Saudi Arabia, offering valuable insights for future projects and contributing significantly to energy conservation.

**Keywords:** concrete compressive strength; life cycle assessment; sustainability; Saudi Arabia; building design



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## 1. Introduction

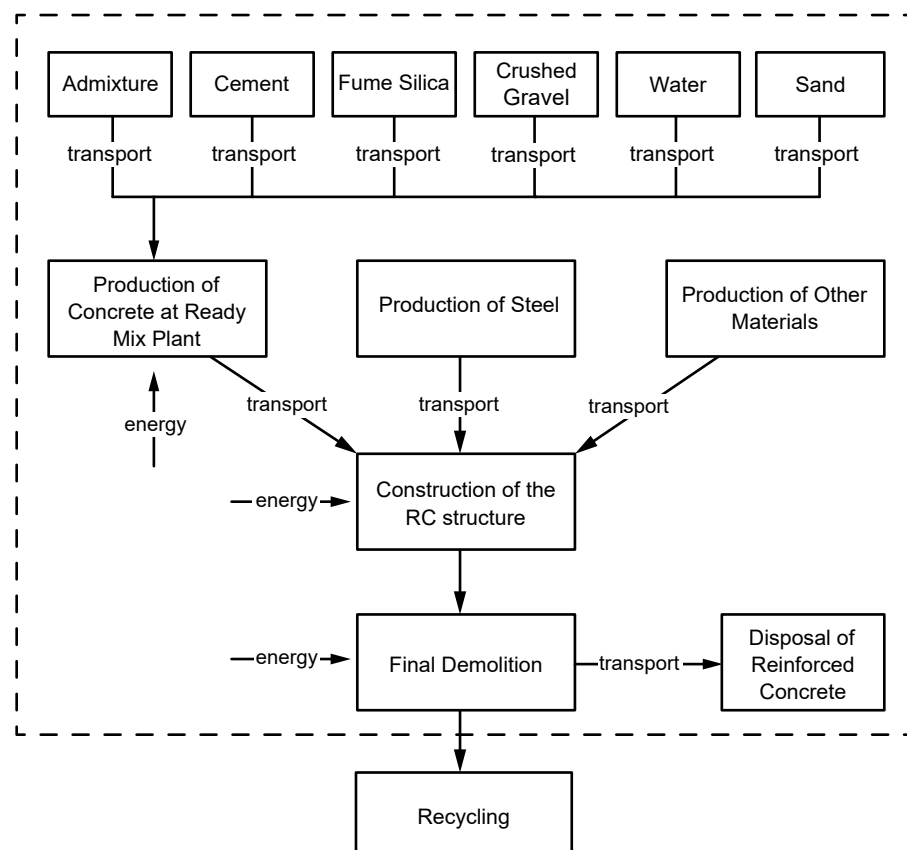
The Saudi Vision 2030 adopts comprehensive improvement standards across all areas of Saudi society, aiming to reduce carbon emissions resulting from the manufacturing of materials related to building construction [1]. These emissions are expected to decrease by 30% and reach net-zero status by 2060. The urgency has arisen as countries worldwide gradually focus more on decarbonizing their economies [2]. The annual growth rate of cement production is currently 4%, owing to the rapid increase in construction in developing countries [3]. Sustainable development and construction are becoming increasingly important as environmental concerns grow. The building sector accounts for roughly 40% of global energy consumption and more than 30% of global greenhouse gas (GHG) emissions. For many years, concrete has been used to build long-lasting bridges, roads, building structures, medical facilities, housing, and commercial buildings to provide social infrastructure, promote prosperity, and aid in operational facility development. Concrete,

as a widely used construction material, has a significant impact on sustainability [4]. While environmental responsibility is undoubtedly important in construction, any method of construction must also be socially responsible and economically viable. To be truly sustainable, a building material must address all three of the aforementioned considerations [5,6].

The Kingdom of Saudi Arabia (KSA) has a large and rapidly growing building sector that heavily contributes to the country's energy and environmental stresses [7,8]. However, the KSA has yet to adopt building sustainability standards and integrate life cycle assessment (LCA) into construction practices to address environmental challenges [9]. The lack of adoption stems from the newness of the LCA concept in the Saudi construction industry. Furthermore, there is a clear gap in academic research regarding LCA studies in the building sector of the KSA [10–12]. Among the G20 group of countries, the KSA now ranks as the fourth-fastest reducer of greenhouse gases (GHGs). Since 2010, the KSA's historically rapid rate of emissions growth has been slowing, declining from an approximate 10% annual increase in 2010 to about 5% between 2011 and 2015. Saudi Arabia's CO<sub>2</sub> emissions and percentage of annual change stabilized in 2016 and 2017, culminating in a 2.7% decrease in 2018 [2].

The building construction sector globally, as well as in the KSA, accounts for approximately 40% of annual energy consumption. This sector is responsible for about 40% of global resource use, employs more than 10% of the workforce, and produces up to 40% of the solid waste worldwide. Additionally, it is a major contributor to CO<sub>2</sub> emissions, accounting for nearly 30% of all energy-related greenhouse gas (GHG) emissions. The production of concrete emits a substantial amount of CO<sub>2</sub>, from material production to the manufacturing stage, primarily due to the cement manufacturing process. According to the Second Greenhouse Gas Emissions Report 1, in the KSA, each ton of cement releases about 0.3 tons of CO<sub>2</sub>, contributing to 8.5% of the CO<sub>2</sub> emissions resulting from the calcination of raw materials and the burning of fossil fuels. Meanwhile, steel production is responsible for 28.9% of CO<sub>2</sub> emissions in the industrial processing and energy sectors [13]. Despite steel being entirely recyclable, the steel remelting process consumes a significant amount of energy. However, there is considerable potential for reducing CO<sub>2</sub> emissions in the building construction sector, especially in both developed and developing countries [14]. The volume of CO<sub>2</sub> emissions (and other GHGs) has been steadily increasing for several decades. Given that concrete is the most widely used man-made material globally, the construction of reinforced concrete structures significantly impacts the environment, primarily due to the use of cement as a binder for concrete and steel as reinforcement [5].

To assess life cycle CO<sub>2</sub> emissions, concrete production operations were divided into three stages: raw material production, material transportation, and concrete manufacture. The environmental effect of each stage was thoroughly evaluated after estimating the energy spent and CO<sub>2</sub> released in each stage. Measures for enhancing environmental conditions were devised based on the assessment results. Figure 1 depicts a flowchart of the concrete's life cycle, from the building contractor placing an order for ready-mixed concrete to the reception of the concrete at the construction site [5]. Based on the causes impacting the building environment in the KSA, this study studied a variety of specific variables, including compressive strength, EC, and cost. Not only does the construction sector consume a lot of energy and emit a lot of pollution, but it also accounts for a sizeable proportion of the total world CO<sub>2</sub> emissions [15].



**Figure 1.** Reinforced concrete production system [5] (Reprinted/adapted from Journal of Cleaner Production, Vol 172, Garcez, M.R., Rohden, A.B. and De Godoy, L.G.G. The role of concrete compressive strength on the service life and life cycle of a RC structure: Case study, Pages No. 27–38, Copyright (2018), with permission from Elsevier).

The simplified life cycle assessment (LCA) technique is a way of delivering a short yet informative study of the environmental consequences associated with a product, process, or service across its full life cycle [16–19]. Compared to typical complete LCAs, which may be resource-intensive and time-consuming, simplified LCAs shorten the assessment process by focusing on major impact categories and employing simplified models and data inputs. These simplified techniques frequently use tools like screening life cycle assessments or streamlined life cycle inventories to analyze environmental impacts, making them more accessible to small firms and projects with limited resources. While simplified approaches may not capture all of the intricacies of a thorough LCA, they nonetheless provide useful decision-making insights and can assist identify areas for improvement in environmental performance [20]. It has been employed in a range of studies in different applications of building/construction engineering and is a widely accepted approach [21]; for example, Hernández et al. [22] used it for assessing a new structure system, Hou et al. [23] used it for assessing cementitious composite materials (mixture design), and Eleftheriou et al. [24] used it for assessing the use of cement bamboo frame technology.

Life cycle assessment (LCA), also referred to as life cycle analysis, serves as a tool for environmental impact assessment (EIA) to guide decisions in building design and construction. However, there is a scarcity of studies that compare various alternatives for the same construction project. In a prior study, the environmental impacts of three distinct four-pavement commercial office buildings were evaluated. These buildings were designed using C25, C50, and C75 concrete, respectively. The primary aim was to showcase the influence of concrete's compressive strength on the service life and overall life cycle

of structural solutions. The analysis of the results primarily focused on construction cost considerations [25,26].

Garcez et al. explored how the compressive strength of concrete affects the environmental impact, construction cost, service life, and durability of reinforced concrete (RC) structures [5]. It demonstrated that C50 concrete showcased better environmental and economic performance compared to C75 while providing a balance between steel and concrete amounts [5]. Goggins et al. investigated methods to manage energy consumption during reinforced concrete manufacturing, showcasing that using ground granulated blast furnace slag (GGBS) as a cement replacement significantly reduced energy consumption in RC structures [27]. Zhang and Zhang utilized a multi-objective optimization approach to design sustainable RC members, emphasizing embodied emissions and costs, demonstrating that a slight cost increase could substantially reduce emissions [6]. Zeinsek and Hajek analyzed strategies for designing RC structures with reduced carbon emissions, highlighting that using lower-strength concrete with a lower clinker content resulted in lower CO<sub>2</sub> emissions [28]. Yoon et al. investigated sustainable design for RC columns, focusing on minimizing construction costs while considering energy consumption and CO<sub>2</sub> emissions, and found a potential 22% reduction in energy consumption and a 63% reduction in CO<sub>2</sub> emissions with a 10% increase in cost [29]. Park et al. explored an assessment of CO<sub>2</sub> emissions based on the compressive strength of concrete mixtures used in construction in Korea, proposing methods for the quantitative assessment of CO<sub>2</sub> emissions at different production and transportation stages [30]. Suhendro explored alternatives to reduce energy consumption and environmental impacts in cement manufacturing, suggesting the use of waste materials or alternative pozzolans to enhance concrete performance [15]. Yeo and Gabbai focused on optimizing structural designs to reduce energy consumption, achieving a 10% reduction in the embodied energy through structural optimization techniques [31]. Park et al. investigated optimizing building operations and designs to minimize CO<sub>2</sub> emissions, specifically concentrating on composite column designs in high-rise buildings, showcasing economical and environmentally efficient approaches [32]. Fraile-Garcia et al. explored high-performance material use in RC column construction, emphasizing geometry, cement type, and concrete strength to reduce costs and emissions while highlighting the impact of execution methods on resource optimization [33].

The relevance of building typology in influencing concrete compressive strength is critical to attaining a sustainable structural design. The building type affects the structural requirements, load-bearing capacity, and durability expectations. Understanding the unique requirements of the building type enables the development of concrete mixes with compressive strength designed to fulfil those demands. Building typologies need varied degrees of strength and resilience. The compressive strength is tailored to the exact needs of the building type, ensuring resource efficiency [34]. This focused method reduces material consumption while retaining structural integrity, which contributes to sustainability objectives [35]. The choice of compressive strength has a direct influence on the construction's environmental imprint [36]. By matching strength with building typology, the concrete mix may be optimized for a decreased environmental effect, considering aspects like embodied carbon and energy usage. Building typology influences the life cycle performance of buildings [37]. The compressive strength must be carefully related to the building type's expected lifetime, maintenance requirements, and general usefulness to ensure long-term sustainability [38]. Finally, understanding the role of building typology in compressive strength allows for a more nuanced and sustainable approach to structural design. This acknowledgment guarantees that concrete compositions are customized to the individual demands of each building type, maximizing both performance and environmental effect [5,39].

The research focuses on a hotel building in the eastern region of Saudi Arabia, specifically Dammam. This hotel has 12 stories, 1280 inhabitants, and an average floor space of 2632 m<sup>2</sup>. The structure is divided into four separate zones, from the basement to the top, each with twenty columns of three types: exterior, internal, and corner. This division sets

the study's goals, with a focus on safety and cost efficiency. The study is consistent with the Saudi Building Code (SBC) 301, 302, and 304 [40–42], notably the concrete column design standards. Adherence to these criteria provides the foundation for guaranteeing structural integrity while efficiently controlling project expenses.

This study diverges by examining the environmental impact concerning concrete compressive strength in a larger-scale setting, specifically a hotel construction project situated in the eastern province of KSA [43]. The primary objective of this study is to assess various concrete designs with differing compressive strengths, aiming to identify the most optimal design in terms of both environmental impact and cost effectiveness. It is critical to recognize the limits of depending exclusively on economic calculations [44], particularly given that the present pricing of commodities often ignores the environmental implications of their production. While economic factors are important in decision-making, especially in building projects, the environmental consequences of material choices are just as important, if not more so, in terms of sustainability [45]. The inclusion of cost considerations in sustainability materials research not only enhances the practical relevance and applicability of findings but also contributes to broader efforts aimed at mainstreaming sustainability principles in industry practices and policies. By demonstrating the cost viability of sustainable solutions, researchers can catalyze market uptake and incentivize investments in environmentally less-impact practices. Moreover, in the context of Saudi Arabia and similar regions experiencing rapid urbanization and infrastructure development, research that integrates both environmental and economic dimensions is particularly pertinent [46,47]. By addressing the dual imperatives of environmental stewardship and economic prosperity, such research endeavors can serve as catalysts for sustainable development pathways tailored to local contexts and priorities.

To accomplish the primary goal of this study, an exhaustive analysis will rigorously focus on measuring and refining concrete compressive strength, an essential process ensuring the precise calibration that is critical for upholding structural integrity and optimal performance within construction settings. Simultaneously, meticulous calculations will be applied to compile the bill of quantities (BOQ), delineating the required volumes of concrete (measured in cubic meters,  $m^3$ ) and steel (measured in tons) essential for strategic resource planning and facilitating seamless construction operations. Central to this endeavor is the evaluation of the embedded carbon coefficient (ECC) for each constituent ingredient incorporated in diverse concrete mixtures. This strategic calculation deeply examines the carbon footprint associated with individual components, offering invaluable insights into their environmental impact. In conjunction, the study will meticulously calculate the total embedded carbon (EC<sub>total</sub>) for each concrete mixture utilized, consolidating the collective environmental footprint of both concrete and steel components and providing a holistic perspective on their environmental impact. Moreover, an intricate and detailed cost analysis will be undertaken to thoroughly assess the financial implications of employing each concrete and steel mixture. This comprehensive evaluation aims to offer comprehensive insights into the financial viability and cost effectiveness of various formulation options available for construction materials. Finally, integrating the identified optimal compressive strength parameters, the study will ingeniously design a concrete mixture. This formulation aims to strike a delicate balance between economic feasibility and environmental sustainability, presenting a tailored solution specifically crafted for this building project.

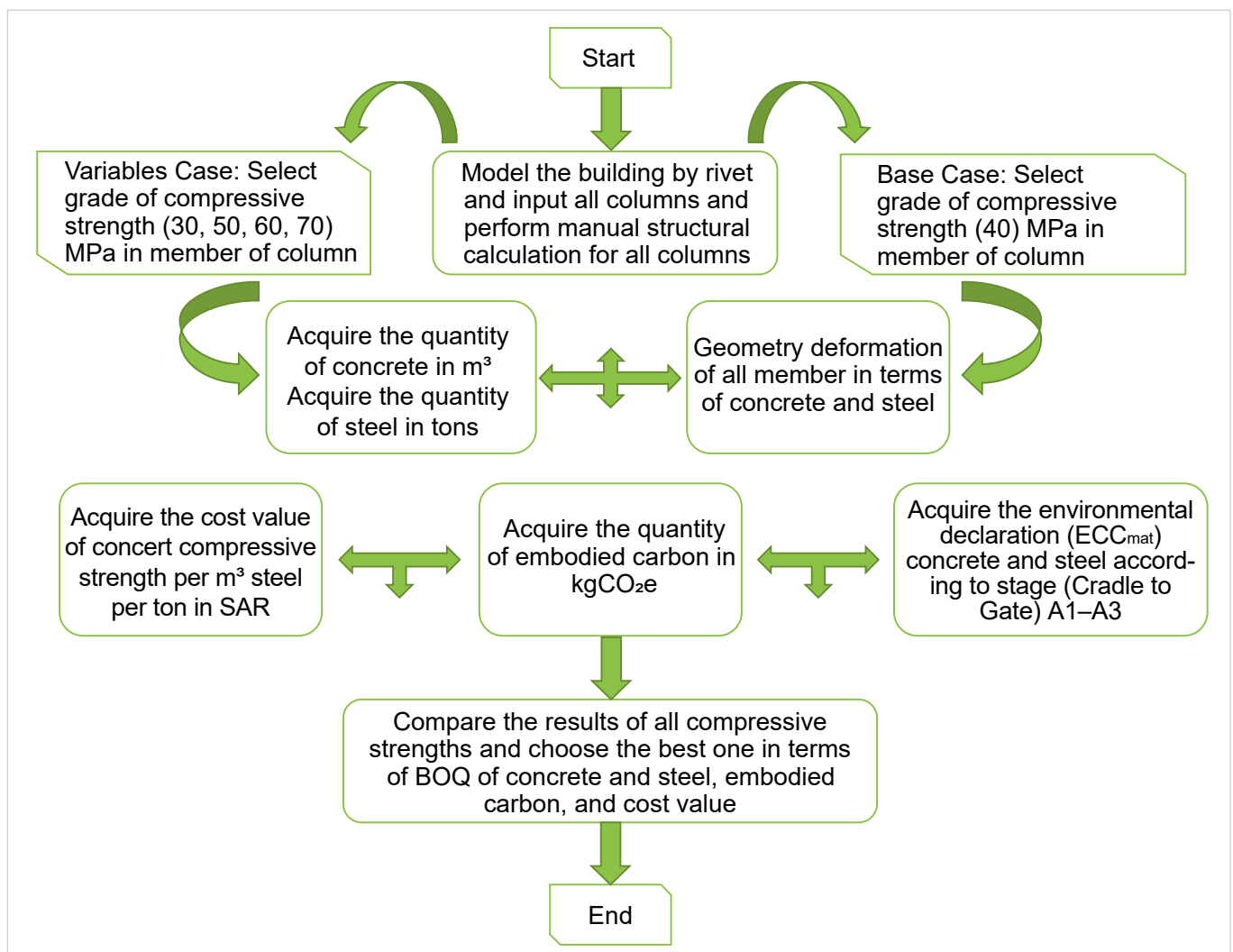
## 2. Material and Methods

### 2.1. Overview

The structural design process for a building begins with the input of key data such as building characteristics, location, drawings, design parameters with corresponding values, compressive strength type, and material environmental declarations. Through a meticulous structural design focused on columns and analysis of geometric deformation, the process calculates the required quantities of concrete in cubic meters and steel in tons. The output of this process includes the environmental impact, measured as the quantity of embodied

carbon in kilograms of CO<sub>2</sub> equivalent, representing the total carbon emissions associated with materials and processes. Additionally, the cost value of concrete compressive strength mixtures is determined, encompassing material costs, labor, and other relevant expenses. This comprehensive approach ensures a balanced consideration of both environmental sustainability and economic factors in the construction of the building.

Figure 2 depicts the visual representation of the research approach used in this study. It entails a methodical approach that includes crucial factors such as building attributes, location, drawings, and structural design, with an emphasis on columns. The collection of building-related data and structural design parameters is the first step in the process. This information is used as input for the following modeling and calculation step, which includes comprehensive estimates of concrete and steel amounts in cubic meters and tons, respectively. The process concludes with the development of critical outputs, such as the quantification of embodied carbon and energy, which provides insight into the environmental effect. Furthermore, the approach calculates the cost value in Saudi Riyals (SR) related to the building of columns. This schematic serves as an important visualization, outlining the full strategy adopted in this study, from data collection to estimated conclusions relating to embedded environmental effects and building costs [13,14].



**Figure 2.** Flowchart of current methodology.

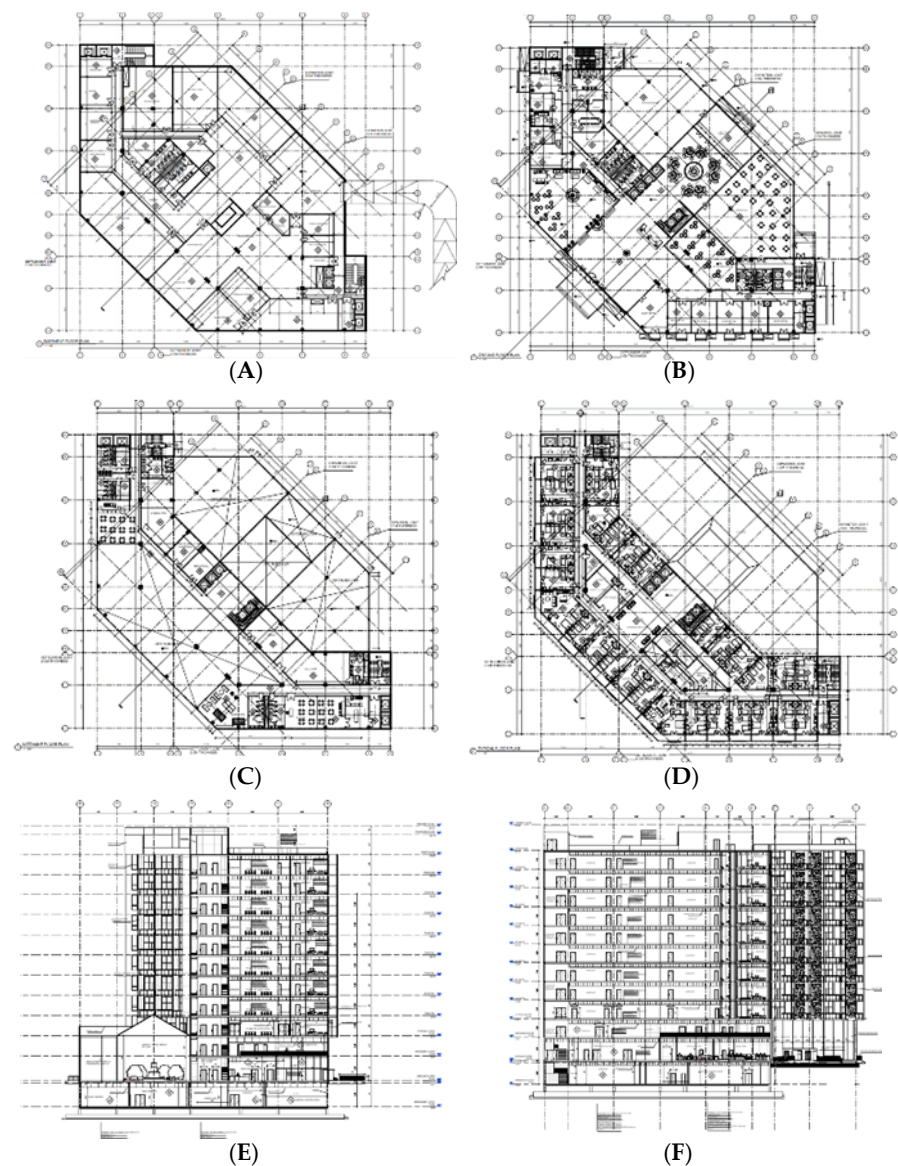
## 2.2. Buildings Characteristics

This study focused on a hotel building situated in the eastern province of Saudi Arabia in the city of Dammam. Table 1 encapsulates the comprehensive general details concerning

this specific building, offering a detailed breakdown of crucial information that is pertinent to the objective of the study. Figure 3 shows the architectural plans and sections used in this study.

**Table 1.** General building information.

| Parameter          | Value                                                                                      |
|--------------------|--------------------------------------------------------------------------------------------|
| Type of Building   | Hotel                                                                                      |
| No. of Floors      | 12 floors                                                                                  |
| No. of Occupants   | 1280                                                                                       |
| Typical Floor Area | 2632 m <sup>2</sup>                                                                        |
| Floor Height       | Basement floor: 4.5 m; ground floor, first, and second floors: 4.8 m; typical floor: 3.9 m |
| No. of Rooms       | 280 rooms                                                                                  |



**Figure 3.** Architectural layout of building considered in this study. (A) basement floor plan; (B) ground floor plan; (C) mezzanine floor plan; (D) typical floor plan; (E) section A–A; (F) section B–B.

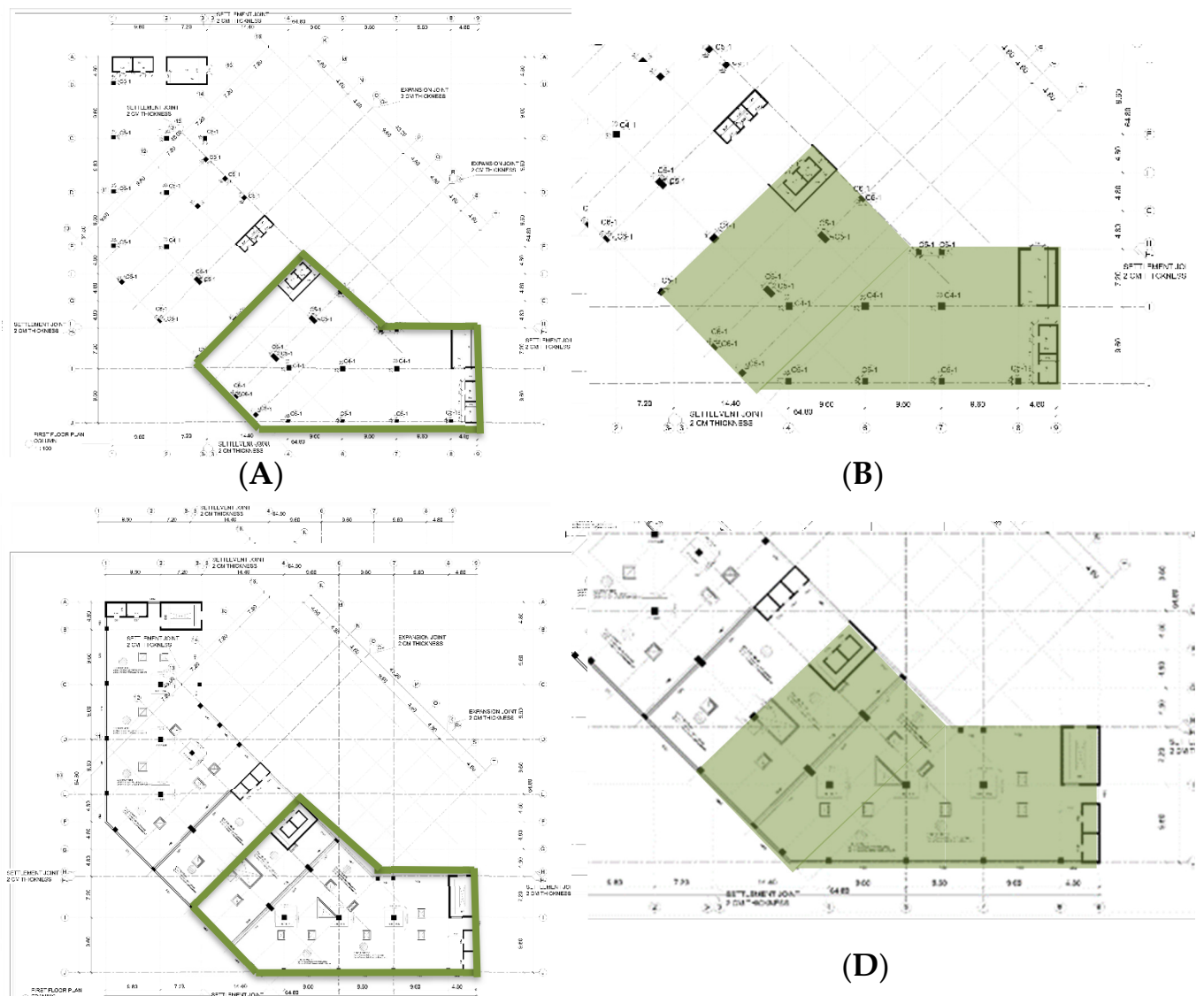
### 2.3. Building Drawings (Zone of Work)

According to the statistics in Figures 4 and 5, the research focuses on a work space with 12 floors and a flat plate as the structural system. These images reflect the architectural and structural layout of building, displaying the design features, floor layouts, and structural configurations connected with the flat plate system across the 12-story structure.



**Figure 4.** Architectural layout of building considered in this study (zone of work). (A) architectural layout of ground floor; (B) zone of work; (C) architectural layout of typical floor; (D) and zone of work.

Table 2 further enhances the research by providing extensive information on key building factors that are important for analysis or assessment. Furthermore, Table 2 most certainly includes a detailed summary of key factors relevant to the building under consideration. This table provides important information about the hotel's features and structural aspects. It includes information on the building type, floor count, zoning arrangement, column count per floor, and the various kinds of columns used throughout the structure. These characteristics have a considerable influence on the hotel's design, functioning, and stability by determining its architectural and structural elements. The number of floors, zoning layout, and column kinds, for example, all have an impact on the building's internal organization, load-bearing capacity, and overall architectural design.



**Figure 5.** Structural layout of building considered in this study (zone of work). (A) columns and grid of typical floor; (B) zone of work; (C) framing of typical floor; and (D) zone of work.

**Table 2.** Zone of work parameters.

| Parameter        | Value                                                                                                                  |
|------------------|------------------------------------------------------------------------------------------------------------------------|
| Type of building | Hotel                                                                                                                  |
| No. of floors    | 12 floors                                                                                                              |
| No. of zones     | Four zones: basement to first floor; first floor to fourth floor; fourth floor to seventh floor; seventh floor to roof |
| No. of Columns   | 20 columns on each floor                                                                                               |
| Column types     | Three types: external; internal; corner                                                                                |

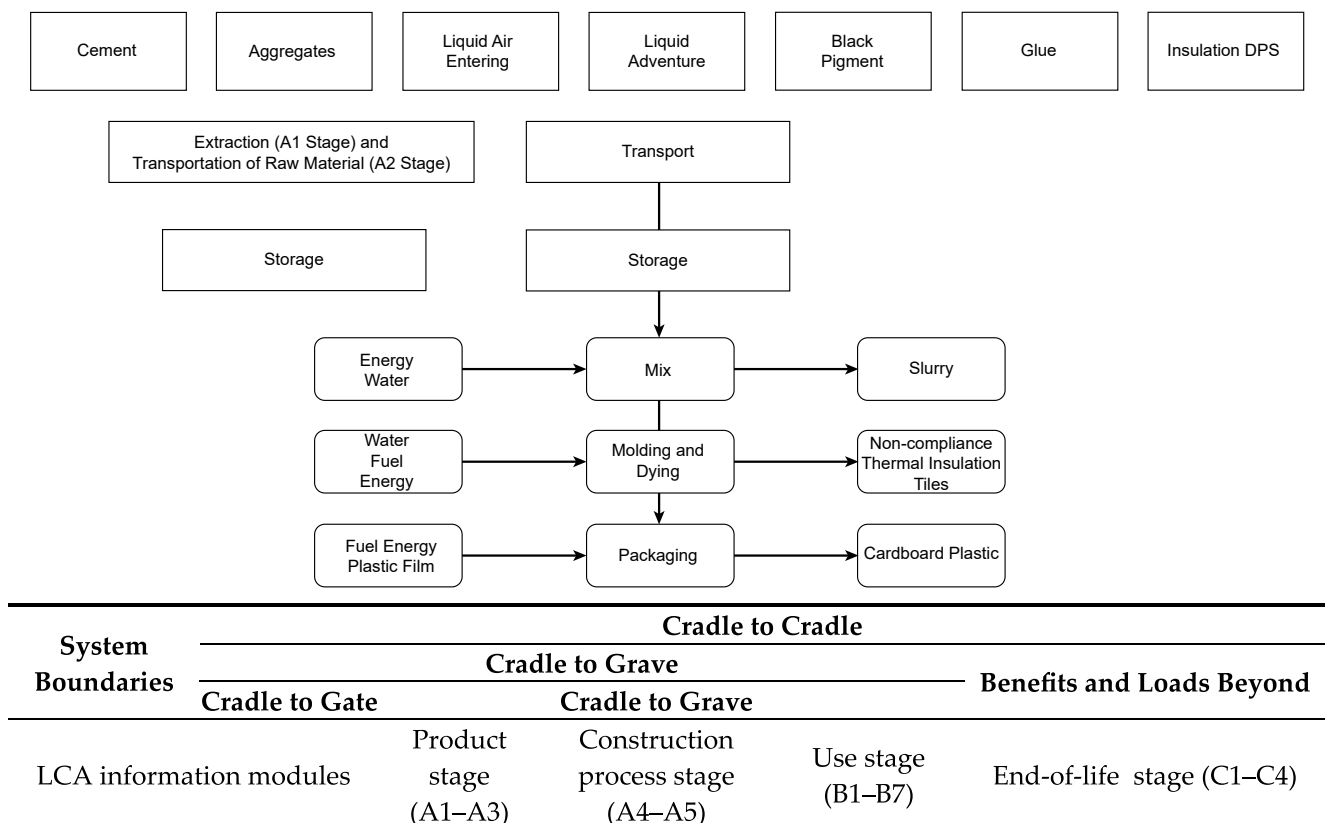
#### 2.4. Environmental Impact Assessment (EIA)

In this research, the final design was developed using Environmental Impact Assessment (EIA) coefficients of materials and the bill of quantities (BOQ). The research used this method to examine the environmental effects from cradle to gate in order to select the best scenario. This approach entails assessing the whole environmental effect of materials from their extraction or production (cradle) until their arrival at the building site (gate).

The research attempted to optimize the design by addressing the ecological footprint of the building materials used by incorporating EIA coefficients, which encompass the environmental effects of different materials, and utilizing the BOQ. Such a method allows for better informed decision-making, enabling the most ecologically friendly design among the possibilities to be chosen. This technique is consistent with current procedures for analyzing the environmental effects of building projects and highlights the need to incorporate ecological considerations into design choices [48].

#### 2.4.1. System Boundaries

Figure 6 illustrates the system boundaries of the current study. The cradle-to-gate assessment approach measures a product's environmental impact from its place of origin (cradle) to the point at which it departs the production site (gate) before reaching the customer. This method entails examining the product's usage and disposal stages. Environmental Product Declarations (EPDs), especially those used in business-to-business situations, are built on such evaluations. This system, which employs life cycle inventory (LCI), enables a full study of the implications before a company's resource acquisition. Companies may then add transportation and production phases to provide cradle-to-gate values for their goods, guaranteeing a comprehensive knowledge of their environmental effects across their full life cycle [49].



**Figure 6.** System boundaries of current study.

#### 2.4.2. Life Cycle Assessment (LCA)

A life cycle assessment comprehensively evaluates a product, process, or service's environmental impacts across all stages of its life cycle [50]. It begins with raw material extraction and processing (cradle), traverses manufacturing, distribution, and utilization, and concludes with recycling or disposal (grave). Some simplifications on building LCA studies have been proposed to produce findings of comparable quality to thorough evaluations

with less effort. A building's life cycle typically includes three major stages: production, management, and destruction [51].

In the context of this study's analysis of a hotel building's environmental impact, Figure 6 outlines the LCA inputs employed, utilizing the building's bill of quantities (BOQ) and EPDs obtained from manufacturers' websites, complemented by interviews with local construction firms. These inputs informed the modeling of each life cycle stage, aiming to represent the Kingdom of Saudi Arabia's (KSA) construction processes for the specific building type under examination. Moreover, LCA examines various environmental facets and potential impacts spanning the entire life cycle (cradle-to-grave), including resource utilization, impacts on human health, and ecological consequences. This comprehensive assessment allows for a thorough understanding of the environmental implications associated with the entire life span of the analyzed product or structure [52].

#### 2.4.3. Stages of Life Cycle

The life cycle assessment stages are product stage (A1–A3), construction stage (A4, A5), use stage (B1–B7), end-of-life stage (C1–C4), and supplementary information (D) [53].

A1–A3: Aggregated module covering raw material extraction and processing, transportation to manufacturer, and manufacturing. It includes materials, energy provision, and waste processing until end-of-waste or final residue disposal at the product stage. This assessment solely focuses on the building and its components, excluding furniture or appliances.

A4–A5: Encompasses losses during construction—transport to building site (A4) and installation into building (A5).

B1–B5: Operation and maintenance during the building's life cycle—use/application, maintenance, repair, replacement, and refurbishment.

B6–B7: Energy and water use during operation, covering heating system operation and building-related services.

C1–C4: Concerns the end-of-life phase—de-construction/demolition, transport to waste processing, waste processing for reuse/recovery/recycling, and disposal.

D: Evaluation of reuse, recovery, and/or recycling potentials, evaluating net impacts and benefits.

These stages meticulously analyze various aspects, ranging from material extraction and manufacturing to building operation, maintenance, and eventual disposal or recycling potential.

### 2.5. Processing of Input Data

#### 2.5.1. Simulation

This study implemented a multifaceted methodology to holistically evaluate the environmental impact and energy consumption of a construction project. Beginning with the creation of a detailed project model using Revit 2019, the process moved into meticulous structural calculations and column section delineations as outlined in Section 2.5.3. Following this, precise calculations were made to ascertain the concrete and steel quantities required for specific building members, as detailed in Section 2.6. To gauge the environmental impact accurately, this study used a method involving the determination of the environmental impact (EC) by considering various compressive strengths of concrete and steel. This assessment was conducted using the ICE (input change effect) method, allowing for a comprehensive understanding of the materials' ecological footprints. Subsequently, a simulation was executed, incorporating input parameters and collecting pertinent data for analysis. Moving beyond mere quantitative evaluations, this study undertook a comprehensive cost assessment, factoring in the considered cases [18,54]. Finally, an optimization process ensued, leveraging insights gleaned from energy consumption metrics and potentially other relevant factors. This systematic and comprehensive approach, starting from initial design and calculations, through material quantification, environmental impact assessment, simulation, cost analysis, and concluding with the selection of an optimal

scenario, aimed to integrate structural, environmental, and cost considerations into the decision-making process.

### 2.5.2. Determination of Environmental Impact

The environmental impact of construction materials, expressed in kilograms of CO<sub>2</sub> equivalent (kgCO<sub>2</sub>e), was derived from the environmental characterization coefficients (ECCs) denoted in either kilogram of CO<sub>2</sub>e per ton or cubic meter of the respective construction materials. The calculation for determining the environmental impact (EC) in kgCO<sub>2</sub>e for the construction materials follows a straightforward methodology based on the ECC [55].

$$EC \text{ (kgCO}_2\text{e)} = ECC \times \text{Quantity of Material Used} \quad (1)$$

where

- EC (kgCO<sub>2</sub>e) represents the environmental impact in kilograms of CO<sub>2</sub> equivalent.
- ECC signifies the environmental characterization coefficients measured in kgCO<sub>2</sub>e per ton or per cubic meter of the specific construction material.
- “Quantity of Material Used” denotes the amount of the respective construction material utilized in the project, measured in tons or cubic meters.

### 2.5.3. Performance Index

The performance indices considered in this study are as follows:

- BOQ for concrete per m<sup>3</sup> and steel per ton.
- ECC<sub>total</sub>, which is the EC coefficient for concrete per kgCO<sub>2</sub>/m<sup>3</sup> and EC coefficient for steel per kgCO<sub>2</sub>/ton.
- EC for each parameter per kgCO<sub>2</sub>e.
- Ratio of constituent materials in mixture.
- Cost value of each mixture used (SAR).
- LCA stages (cradle-to-gate) A1–A3.

## 2.6. Study Tools

The investigation into compressive strength ratios involved a comprehensive methodology. An online resource, Circular Ecology [50], was utilized for data collection purposes. Manual calculations were performed to explore Environmental Product Declarations (EPDs) for various mixtures featuring distinct compressive strengths. Through a manual design process, quantities for concrete columns, encompassing concrete and steel, were determined, and an optimal quantity was chosen. This study delved into five different compressive strengths to evaluate the consistency of results under varying design criteria. A meticulously detailed procedure was adopted to ensure accurate estimation of the environmental performance of each mixture. The process encompassed a thorough examination of how differing compressive strengths impacted the overall environmental aspects of the materials and structures involved [55].

### 2.6.1. Study Variables

This pivotal dataset entailed various grades and their corresponding F<sub>c</sub> values.

- Standard grade: C30 (30 MPa).
- Base case: C40 (40 MPa).
- High grade: C50 (50 MPa).
- High grade: C60 (60 MPa).
- High grade: C70 (70 MPa).

These delineated concrete grades, each with their designated F<sub>c</sub> value, served as fundamental parameters influencing subsequent evaluations and analyses performed within the study framework. This comprehensive assortment of concrete grades was pivotal in gauging and comparing the environmental impact, structural performance,

and overall efficacy across different design criteria and compressive strengths employed throughout the research.

### 2.6.2. Structural Analysis

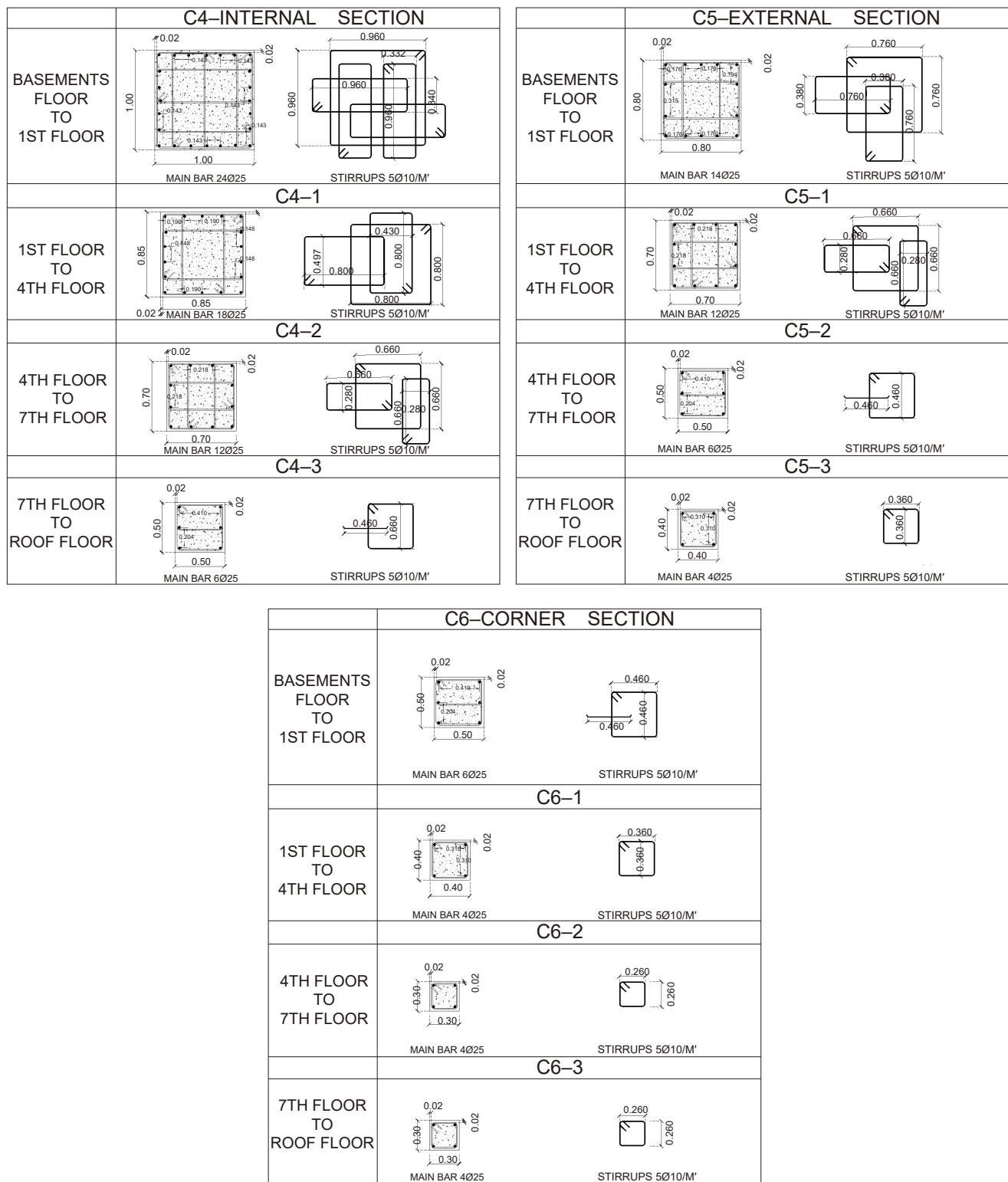
The objectives of the study begin by segmenting the considered building into four distinct areas, each receiving individualized design attention. Adhering to the safety and cost-efficiency paradigms, the research leveraged the stipulations delineated within the Saudi Building Code (SBC) 301, 302, and 304 pertaining to the design specifications for concrete columns, as encapsulated within Table 3 [40]. This strategic adoption of the Saudi Building Code standards formed the cornerstone for ensuring structural integrity while mitigating expenses within the project framework. The evaluation encompassed computing extensions and total loads exerted on the columns across various concrete mixtures, facilitating meticulous assessments to ascertain feasibility and adherence to defined parameters. Following the parameter inputs, comprehensive data compilation ensued, enabling meticulous scrutiny to validate calculability. Subsequently, the bill of quantities was meticulously collated, elucidating the precise quantum of steel and concrete requisite for optimal project execution. This systematic approach was pivotal in aligning structural robustness, cost effectiveness, and compliance with established industry standards.

**Table 3.** Design parameters and corresponding values.

| Parameter                                       | Value                                                        |
|-------------------------------------------------|--------------------------------------------------------------|
| Ultimate load of slab                           | 23.84 kN/m <sup>2</sup>                                      |
| Slab load acting on column                      | Slab load $\times$ area covered by column                    |
| Self-weight of column                           | Depending on member dimensions (breadth (b); thickness (t))  |
| Safety factor for design, U (for column)        | 1.4                                                          |
| Compressive strength of concrete ( $f_c$ )      | 40 MPa for base case; 30, 50, 60, and 70 MPa for other cases |
| Yield strength of steel reinforcement ( $f_y$ ) | 420 MPa                                                      |
| Concrete density ( $\rho_c$ )                   | 2400 kg/m <sup>3</sup>                                       |
| Floor height                                    | 3.9 m; 4.275 m                                               |
| No. of stories                                  | According to zone                                            |
| Column type                                     | Tied column                                                  |
| Reinforcement ratio ( $\rho_g$ )                | 0.01                                                         |
| General equation (PU)                           | $0.8 \times 0.7 [0.85f_c' (1 - \rho_g) + \rho_g f_y] A_g$    |
| Area of required reinforcement ( $A_s$ )        | Calculated as per SBC302;<br>$A_s = \rho_g \times A_g$       |
| Area of required concrete ( $A_g$ )             | Calculated according to PU value                             |
| Rebar diameter                                  | Ø25 for main bars; Ø10 for tie bars                          |
| Area of diameter used ( $A_b$ )                 | According to type of rebar                                   |
| No. of bars (N)                                 | According to $A_s$ and $A_b$                                 |
| Spacing of ties                                 | Calculated as per SBC302                                     |

### 2.6.3. Structural Sections

Following the design phase of the columns, as illustrated in Figure 7, meticulous efforts were dedicated to compiling section tables for each designated area. The deployment of columns involved strategic positioning along the axes, precisely orchestrated to circumvent spatial conflicts and uphold the architectural functionality within the space.



**Figure 7.** Details of columns used for base case.

#### 2.6.4. Optimal Design and SBC

This study meticulously assessed structural elements by prioritizing standards and variables, crucially emphasizing the loads exerted on columns to prevent system failures or collapses. Additionally, carbon quantities linked to the materials in the concrete mix were

computed to guide optimal material selection. Moreover, adherence to design limits and requirements for concrete sections and reinforcement was aligned with SBC 304.

#### 2.6.5. Analysis of Embodied Carbon Coefficient (ECC)

The assessment encompassed the EC calculation from raw material manufacturing to the transportation of varied concrete mixtures. This computation accounted for diverse components within the concrete mix, such as cement, aggregate, sand, and other materials. The process involved utilizing an online calculator available on Circular Ecology, specifically within the ICE database, which offers a tool dedicated to determining EC values for concrete formulations [56].

#### 2.6.6. Embodied Carbon Factor for Materials

Table 4 outlines the EC coefficients for material production, showcasing distinct coefficients across various materials. Cement notably exhibits the highest coefficient, signifying a more substantial environmental impact, while water registers the lowest coefficient, indicating a relatively lower environmental impact in its production [57].

**Table 4.** ECC for each material [58–60].

| Materials              | Embodied Carbon: kgCO <sub>2</sub> /kg | Notes                                                                                                                                                                                                                                                         |
|------------------------|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Clinker                | 0.97                                   | Extrapolated from EPD for average UK cement. EN 15804 EPD number EPD-MPA-20170159-CAG1-EN.                                                                                                                                                                    |
| Gypsum                 | 0.002536                               | Source: Oekobaumat-Gypsum stone (CaSO <sub>4</sub> -Dihydrate); grinded and purified product.                                                                                                                                                                 |
| Limestone              | 0.01577                                | Source: Oekobaumat-Crushed stone 0/2; grain size: 0/2.                                                                                                                                                                                                        |
| Aggregates             | 0.00747                                | ICE V3.0; weighted average of aggregates.                                                                                                                                                                                                                     |
| GGBS                   | 0.0416                                 | EN 15804 EPD; number: MRPI code 20.1.00033.005.                                                                                                                                                                                                               |
| Fly ash                | 0.004                                  | Based on 2 data points.                                                                                                                                                                                                                                       |
| Water                  | 0.00034400                             | Defra 2018. Water supply only; e.g., excludes water treatment, because the water ends up in the product.                                                                                                                                                      |
| Admixture              | 1.67                                   | Average of six EPDs; see calculations below.                                                                                                                                                                                                                  |
| MAC                    | 0.002536                               | Minor additional constituent materials used in cement. They are assumed to have the same impact as gypsum.                                                                                                                                                    |
| Cement, OPC            | 0.912                                  | Modelled with 94% clinker, 5% gypsum, 1% MAC.                                                                                                                                                                                                                 |
| Limestone fines        | 0.01577                                | Source: Oekobaumat-crushed stone 0/2; grain size: 0/2.                                                                                                                                                                                                        |
| Natural pozzolanic ash | 0.00747                                | For example, volcanic ash. There are no carbon footprint data. However, the production process is comparable to that of aggregates and sand, and consists of extraction and crushing; therefore, the impact was assumed to be the same as that of aggregates. |
| Lime, hydrated         | 0.891                                  | Generally used in mortars. Source: EuLa, LCI of European lime production.                                                                                                                                                                                     |
| Lime, quicklime        | 1.136                                  | Generally used in cements. Source: EuLa, LCI of European lime production.                                                                                                                                                                                     |

#### 2.6.7. Embodied Carbon Calculator for Steel (ECC)

The carbon steel rebar, sourced from local manufacture (the ITTEFAQ Factory) in Dammam, Saudi Arabia, underwent production by melting scrap within an electric arc furnace (EAF) and subsequent hot rolling processes, according to the environmental product declaration (EPD) [61]. Based on the declaration, it is manufactured from melted scrap metal (recycled 39.2%), then refined to remove impurities, cast in billets, and finally rolled by mill to produce the required shape and dimensions (final product: reinforcing steel). For

the analysis, the unit considered was 1 ton of carbon steel rebar, typical for the concrete elements in commercial buildings. Through processing and utilizing this reinforcing steel, the study assessed the global warming potential (GWP) during (A1–A3), which was 977 in kilograms of CO<sub>2</sub> equivalent. The methodology for determining GWP varied depending on the application and was selected in alignment with prevalent industry practices, standards, and manufacturer recommendations. During the transport and storage of these reinforcing steel products, adherence to typical load-securing requirements was observed.

#### 2.6.8. Environmental Product Declaration

The EPD is a standardized and validated publication that offers clear and comparable information about a product's environmental effects across its full life cycle. It describes different environmental characteristics of the product, such as energy use, emissions, resource consumption, and waste creation, from raw material extraction to disposal or recycling. Table 5 outlines the environmental impact assessment (EIA) at the A1–A3 stage of the life cycle assessment for various concrete mixtures, specifically regarding their embodied carbon.

**Table 5.** Total EC value for each mixture.

| Selected Stage of LCA | Concrete (m <sup>3</sup> ) | Fc' (MPa) | ECC Total Concrete (kgCO <sub>2</sub> e/m <sup>3</sup> ) | Steel (ton)           | ECC Total Steel (kgCO <sub>2</sub> e/ton) |
|-----------------------|----------------------------|-----------|----------------------------------------------------------|-----------------------|-------------------------------------------|
| A1–A3                 | C40                        | 416       | (ECC Total for C40 Concrete)                             | ITTEFAQ Factory (GWP) | 977                                       |
| A1–A3                 | C50                        | 471       | (ECC Total for C50 Concrete)                             | -                     | -                                         |
| A1–A3                 | C60                        | 518       | (ECC Total for C60 Concrete)                             | -                     | -                                         |
| A1–A3                 | C70                        | 554       | (ECC Total for C70 Concrete)                             | -                     | -                                         |
| A1–A3                 | C80                        | 592       | (ECC Total for C80 Concrete)                             | -                     | -                                         |

#### 2.6.9. Compressive Strength of Mixture Components

Table 6 lists the quantities of the concrete mixture components, including cement, gravel, sand, and additives.

**Table 6.** The quantities of the concrete mixture components.

| Compressive Strength of Concrete |                               |                             | Quantities of Concrete Components |                           |                    |                                       |                                     |                               |                                          |
|----------------------------------|-------------------------------|-----------------------------|-----------------------------------|---------------------------|--------------------|---------------------------------------|-------------------------------------|-------------------------------|------------------------------------------|
| Approximate Factory Mix Fc'      | Factory Mix Fcr (28 Days MPa) | Design Composition (Fc MPa) | Cement (kg/m <sup>3</sup> )       | Water (L/m <sup>3</sup> ) | Water/Cement (W/C) | Coarse Aggregate (kg/m <sup>3</sup> ) | Fine Aggregate (kg/m <sup>3</sup> ) | Admixture (L/m <sup>3</sup> ) | Density of Concrete (kg/m <sup>3</sup> ) |
| 40                               | 38.27                         | 30                          | 420                               | 162                       | 0.38571426         | 1111                                  | 768                                 | 1.89                          | 2462.89                                  |
| 50                               | 48.82                         | 40                          | 480                               | 180                       | 0.375              | 1077                                  | 772                                 | 1.54                          | 2510.54                                  |
| 60                               | 59.82                         | 50                          | 530                               | 198                       | 0.373584906        | 1094                                  | 741                                 | 1.9                           | 2564.9                                   |
| 70                               | 70.82                         | 60                          | 570                               | 216                       | 0.378947368        | 1110                                  | 683                                 | 2.1                           | 2581.1                                   |
| 80                               | 81.82                         | 70                          | 610                               | 234                       | 0.383606557        | 1127                                  | 676                                 | 2.5                           | 2649.5                                   |

#### 2.6.10. Comparison between Fc', Fcr', and Fcr

Fc: This denotes the intended or targeted compressive strength of the concrete that needs to be designed.

Fcr: This represents the anticipated or approximate compressive strength of the concrete received from the factory. It tends to be higher than Fc' to compensate for potential losses during transportation, handling, or production issues, as suggested by ACI 318 [62]. It is a precautionary measure to ensure the concrete's strength upon arrival matches or exceeds the design requirements.

Fcr: This is the actual compressive strength of the concrete upon its arrival from the factory. It is also higher than Fc and is adjusted to account for potential losses or discrepan-

cies during transportation and other manufacturing-related issues, according to ACI 318. This value reflects the concrete's real strength once it reaches the site after considering all potential setbacks during transit or manufacturing processes. The conversion of  $F_c'$  into  $F_{cr}'$  is based on the following equations:

$$F_c' < 20.6 \text{ MPa then } F_{cr}' = F_c' + 7.00$$

$$20.6 < F_c' < 35 \text{ then } F_{cr}' = F_c' + 8.50$$

$$35 > F_c' \quad \text{then } F_{cr}' = 1.1F_c' + 5.00$$

## 2.7. Bill of Quantities (BOQ)

The comparison includes evaluating the bill of quantities (BOQ) for each concrete mixture studied. The BOQ specifies the volume of concrete in cubic meters ( $\text{m}^3$ ) and the amount of steel reinforcing in tons. This comparison allowed for an examination of the material needs for each mixture, assisting in determining the differing amounts of concrete and steel required to achieve the structural design parameters at various compressive strengths. These quantities are reported in Table 7 for each combination, assisting in understanding the volume of materials necessary for construction when employing different concrete compositions [63,64].

**Table 7.** Material quantities for each designed concrete.

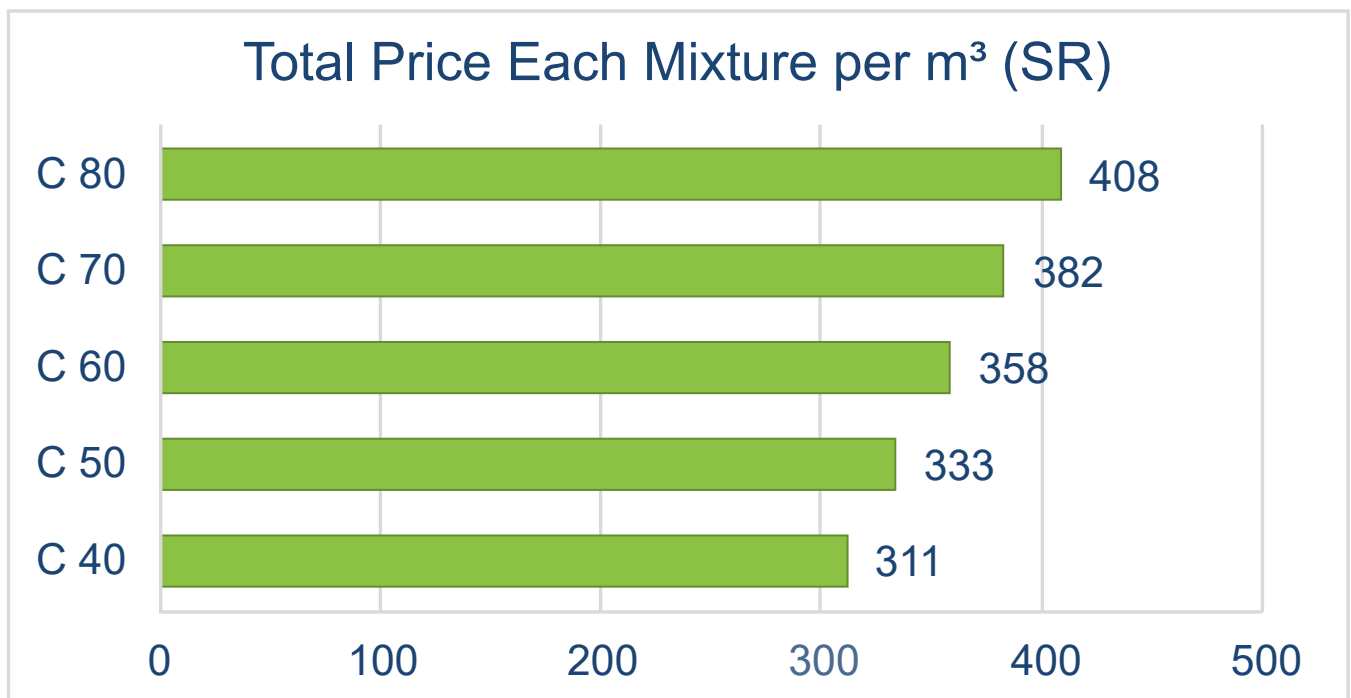
| Designed Concrete | Material                  | Quantity |
|-------------------|---------------------------|----------|
| C 30              | Concrete ( $\text{m}^3$ ) | 169.42   |
|                   | Steel (ton)               | 4.20     |
| C 40 (base case)  | Concrete ( $\text{m}^3$ ) | 124.11   |
|                   | Steel (ton)               | 3.70     |
| C 50              | Concrete ( $\text{m}^3$ ) | 100.5    |
|                   | Steel (ton)               | 2.80     |
| C 60              | Concrete ( $\text{m}^3$ ) | 90.4     |
|                   | Steel (ton)               | 2.30     |
| C 70              | Concrete ( $\text{m}^3$ ) | 73.5     |
|                   | Steel (ton)               | 1.90     |

The BOQ includes the quantities specified for the design of the final member only and does not consider waste or processing requirements for construction.

## 2.8. Cost-Value Ratio

### 2.8.1. Concrete

After researching concrete factories in the KSA, it was found that most factories do not manufacture high-resistance concrete. Therefore, the cost of each type of concrete used in this study was calculated by calculating the cost of the materials in each mixture, the value of waste, and the net profit of the mixture's manufacturer (Figure 8).



**Figure 8.** Cost of each mixture.

Calculations for each component:

- Cement: 18 SAR per 50 kg/bag; sand: 12 SAR/m<sup>3</sup>.
- Coarse aggregate: 52 SAR/m<sup>3</sup>; water: 0.005 SAR/L.
- Total cost of material (cement, sand, coarse aggregate, and water).
- Waste of material in each mixture (10%).
- Company profit for each mixture (25%).
- Total cost of concrete = cost of material, waste, and profit.

These product prices were obtained from market data and by consulting experienced professionals and engineering consultancy firms.

#### 2.8.2. Steel

Upon investigating steel factories in Saudi Arabia, disparities in pricing among various factories were noted. Table 8 illustrates the prices offered by SABIC for steel rebar per ton and per bar. This study specifically opted for 25 mm diameter rebar to attain varying concrete compressive strengths.

**Table 8.** Cost of each rebar diameter.

| Rebar Diameter (mm) | Length (m) | Price per Bar (SAR) | Price per Ton (SAR) |
|---------------------|------------|---------------------|---------------------|
| 16                  | 12         | 69.43               | 3680                |
| 18                  | -          | 87.62               | -                   |
| 20                  | -          | 108.24              | -                   |
| 25                  | -          | 170.16              | -                   |
| 32                  | -          | 283.07              | -                   |

### 3. Results and Discussion

This study aimed to identify the concrete compressive strength that offers both reduced environmental impact and lower cost while enhancing the service life and durability of the reinforced concrete structure. The results presented below outline the environmental impact

and cost analysis for various concrete compressive strengths, comparing their attributes against the base case. The assessment involves comparing the chosen concrete mixtures within the same column zone. These comparisons encompass the quantity of materials used, the associated environmental impact (EC), and the overall cost. The objective is to pinpoint the optimal concrete compressive strength ( $F_c'$ ) that strikes a balance between environmental considerations, cost effectiveness, and structural performance within the specified column zone.

### 3.1. Base Case Simulation Result

The bill of quantities (BOQ) encapsulates crucial details such as the volume of concrete measured in cubic meters ( $m^3$ ) and the quantity of steel measured in tons. The total environmental carbon footprint ( $EC_{total}$ ) considers both the EC coefficient of concrete denoted in  $kgCO_2/m^3$  and that of steel quantified in  $kgCO_2/ton$ . By combining these factors, the  $EC_{total}$  assesses the overall environmental impact, incorporating both concrete and steel quantities in  $kgCO_2e$ . Moreover, the cost estimation encompasses the concrete price per  $m^3$  and the steel price per ton in SAR (Saudi Arabian Riyal). These values form a comprehensive overview of the materials' volumes, their environmental implications, and the associated costs, serving as pivotal factors in assessing the feasibility, environmental impact, and economic considerations within the construction project [65].

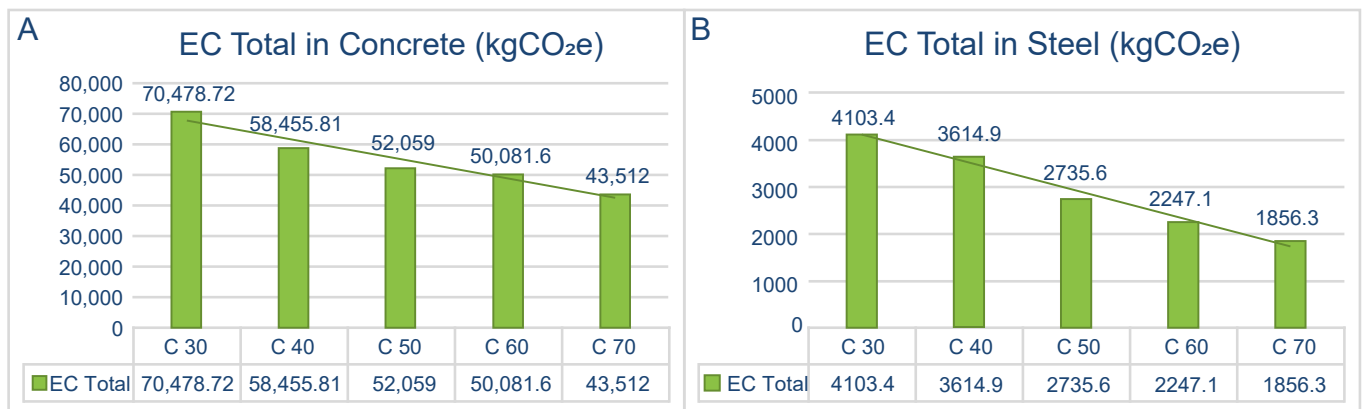
The total environmental impact,  $EC_{total}$ , of concrete amounts to 58,455.81  $kgCO_2e$ , while for steel, it stands at 3614.9  $kgCO_2e$ . In terms of pricing, the concrete's cost is calculated at 41,328.63 SAR, considering a price of 333 SAR per  $m^3$ . Meanwhile, the steel's cost is estimated at 14,892.5 SAR, considering a price of 3680 SAR per ton. The total embodied carbon coefficient ( $kgCO_2/m^3$ ) for concrete was 471, while for steel, it was 977.

### 3.2. Effect of Embodied Carbon on $F_c$

This subsection delves into the significance of embodied carbon in the creation, conveyance, and production phases of concrete mixtures, as well as in the manufacturing process of steel. The embodied carbon (EC) values attributed to concrete and steel represent the cumulative EC during the production stage (A1–A3) within the environmental impact assessment. This assessment highlights the holistic impact assessment encompassing the various stages involved in generating concrete mixtures, such as sourcing raw materials, transportation, and the manufacturing process itself. Similarly, for steel, it encapsulates the EC associated with its production, including factors like melting scrap, the manufacturing process, transportation, and storage. Understanding the EC within these stages is crucial in comprehending the total environmental impact generated by the concrete mixtures and steel used in the construction process. This consideration aids in making informed decisions regarding material selection, optimizing manufacturing processes, and implementing measures to reduce the overall environmental footprint of construction projects [57,66,67].

#### 3.2.1. Carbon Embodied in Concrete and Steel

The illustration in Figure 9 vividly displays the comparative  $EC_{total}$  among various concrete compressive strengths. It notably highlights the substantial variance in  $EC_{total}$ , with C30 showcasing the highest and C70 demonstrating the lowest environmental impact. A nuanced difference is observable between the C50 and C60 mixtures, indicating a relatively close  $EC_{total}$  between these two variants. This graphical representation elucidates the distinct environmental impacts associated with different concrete compositions, emphasizing the pronounced advantage of opting for higher strength mixtures, particularly C70, in minimizing environmental ramifications during construction.

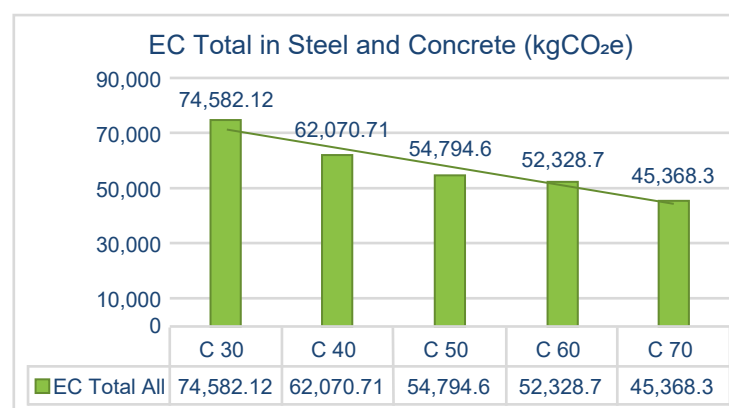


**Figure 9.** EC<sub>total</sub> in (A) concrete and (B) steel.

The visual depiction in Figure 9 highlights the EC<sub>total</sub> pattern among concrete mixtures, with C30 registering the highest value and C70 exhibiting the lowest environmental impact. Notably, mixtures C50 and C60 demonstrate a discernible contrast in embodied environmental impact compared to C30, further emphasizing the role of concrete composition in environmental considerations. This visual representation accentuates the advantage of employing higher strength mixtures, particularly C70, in mitigating environmental footprints during construction processes.

### 3.2.2. Relationship between Compressive Strength and Embodied Carbon and Steel

Figure 10 shows a significant link between the concrete compressive strength and embodied carbon (EC<sub>total</sub>). As compressive strength increases, so does the environmental effect, with C30 having the greatest EC<sub>total</sub> and C70 the lowest. The minimal difference between C50 and C60 shows that both mixes have equal environmental impacts. Understanding this inverse tendency is critical for weighing the benefits and drawbacks of increasing compressive strength vs. increasing embedded carbon content. The increased cement consumption necessary for greater strength combinations adds to the environmental effect, emphasizing the importance of a balanced strategy that takes into account both strength needs and sustainability goals [68].



**Figure 10.** EC<sub>total</sub> in concrete and steel.

### 3.2.3. Percentages of Reduction and Increase in Embodied Carbon

Once all EC ratios for the analyzed concrete and steel mixtures were computed, a comparative assessment was undertaken to evaluate the reduction and increase ratios among them, which is listed in Table 9.

**Table 9.** Percentages of reduction and increase in total EC.

| Compressive Strength (Fc') | Total Embodied Carbon (EC) | Total EC for Used Fc'—Total EC of Base Case | Percentages of Reduction and Increase in Total EC |
|----------------------------|----------------------------|---------------------------------------------|---------------------------------------------------|
| C30                        | 74,582.12                  | 12,511.41                                   | 20%                                               |
| C40 (Base case)            | 56,221.10                  | 0                                           | 0%                                                |
| C50                        | 54,794.60                  | 7276.11                                     | −11.70%                                           |
| C60                        | 52,328.70                  | 9742.01                                     | −15.60%                                           |
| C70                        | 45,368.30                  | 16,702.41                                   | −27%                                              |

The data indistinctly reveal an increase in the C30 mixture, a marginal variation between the C50 and C60 mixtures, and a substantial decrease in the C70 mixture.

### 3.3. Effect of Cost Value on Fc

The importance of cost reduction in concrete mixtures and steel lies in achieving economic efficiency and promoting sustainable practices in construction. Cost reduction measures directly impact project feasibility and the overall budget. When analyzing the rate of reduction in prices, it indicates the potential for savings in construction expenses, which is critical for both short-term project costs and long-term operational expenses.

#### 3.3.1. Cost Reduction for Concrete and Steel

Figure 11 illustrates the cost reductions observed across different concrete mixtures. C30 demonstrates the highest cost reduction among the considered mixtures. C70 reflects the lowest cost among the mixtures, indicating it might be the most cost-efficient option. C50 and C60 show a minor difference in cost reduction, suggesting they may have relatively similar cost efficiency compared to the other mixtures. This depiction of cost reduction across different concrete mixtures signifies the potential financial advantages and feasibility considerations associated with utilizing specific mixtures. It is important to analyze these variations comprehensively, considering not just cost but also environmental impact, structural integrity, and long-term sustainability when determining the optimal choice for a construction project [66,69].

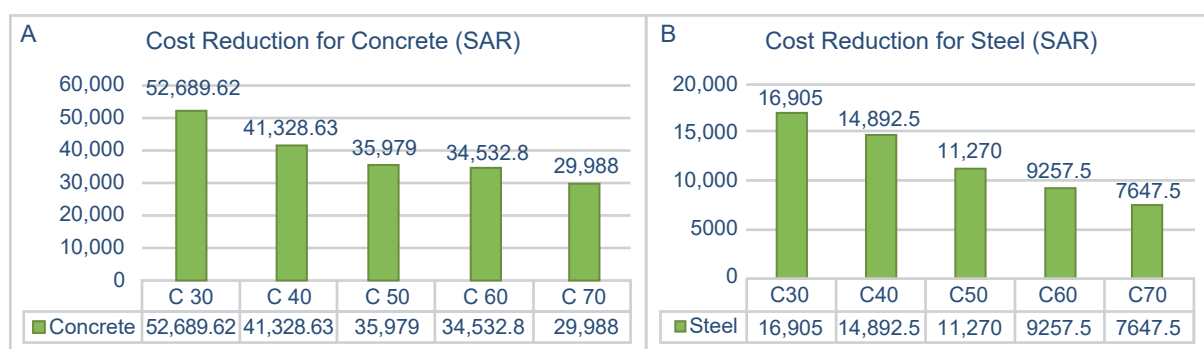
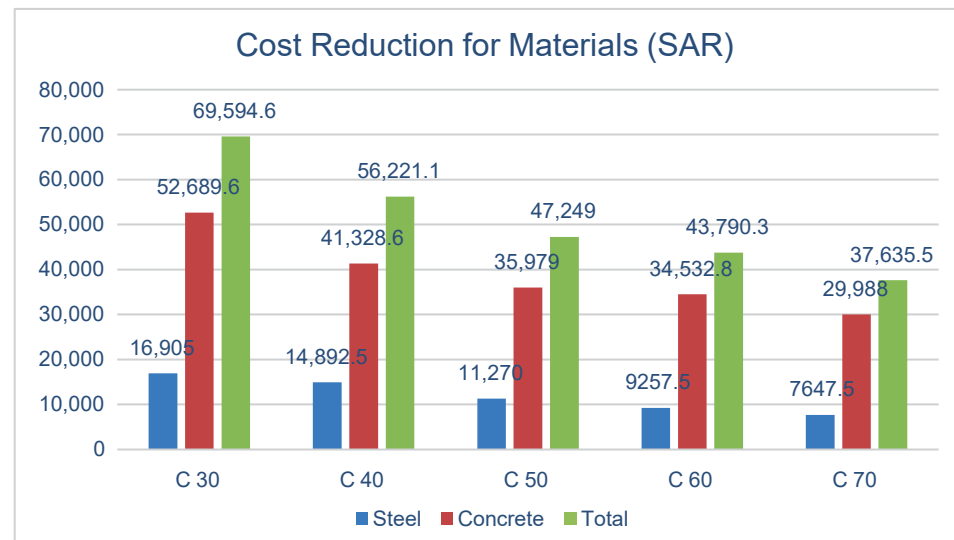
**Figure 11.** Cost reduction for (A) concrete and (B) steel.

Figure 11 depicts the reduction in cost of steel, with C30 indicating the highest reduction in steel costs among the considered mixtures. C70 reflects the lowest steel cost among the mixtures, suggesting it might be the most cost-efficient option concerning steel expenses. C50 and C60 display a notable difference in steel cost reduction, indicating potential distinctions in cost efficiency between these mixtures.

### 3.3.2. Trade-Offs between Compressive Strength and Cost Efficiency

Figure 12 gives useful information on the trade-offs between compressive strength and cost reduction for various concrete compositions.



**Figure 12.** Cost reduction for concrete and steel.

The C70 mixture demonstrates the lowest prices among all mixtures investigated. The C30 mixture reflects the highest prices when compared against the other mixtures considered. The C50 and C60 mixtures show variability in prices when compared to the baseline C40 mixture, indicating potential differences in cost implications between these mixtures. Understanding the cost differences between concrete mixtures is essential in assessing the financial impact of material selection and assisting in decision-making toward an economically feasible and efficient choice for the project's needs. These findings highlight the complexities of decision-making, since increasing compressive strength may come at the expense of cost efficiency. When deciding on the best option for a building project, it is critical to thoroughly analyze these variables, considering not only cost but also environmental effects, structural integrity, and long-term sustainability.

### 3.3.3. Percentages of Reduction and Increase in Cost Value

Table 10 represents the cost change percentages concerning the base case (C40 mixture). Each concrete mixture's cost is compared to the cost of the base case, which remains at 0% change.

**Table 10.** Percentages of reduction and increase in total cost.

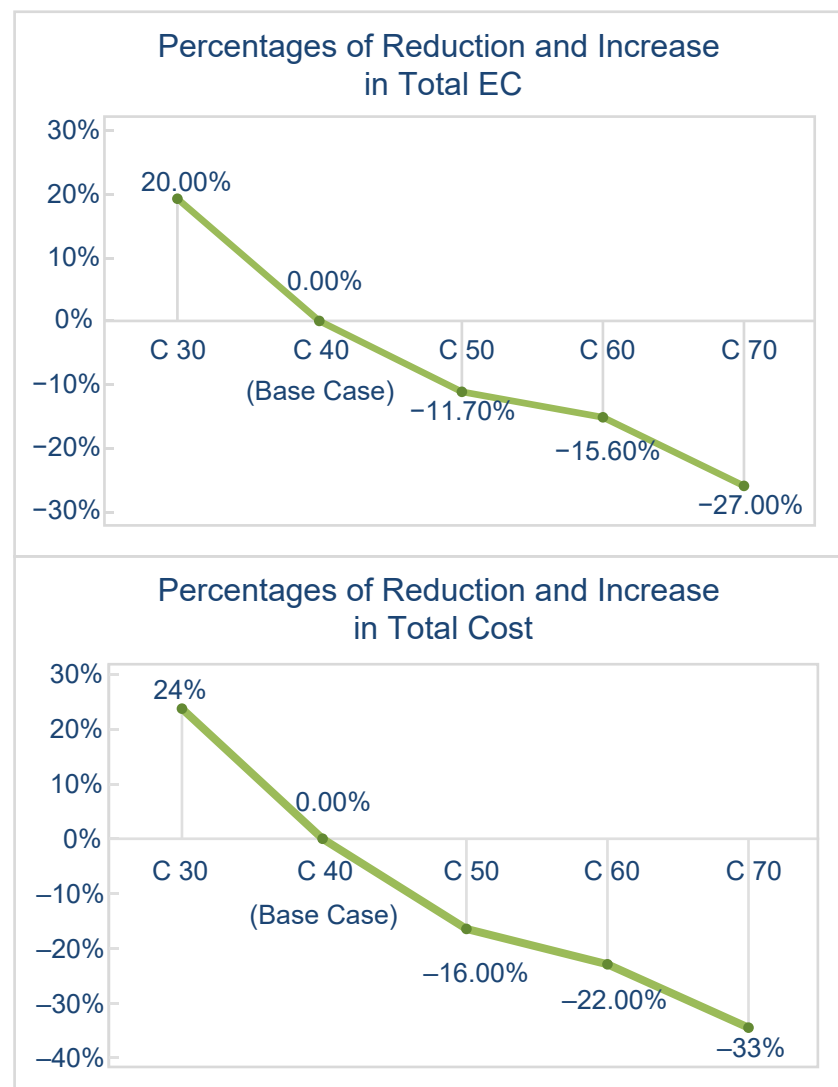
| Compressive Strength (Fc) | Total Cost of Material (SAR) | Total Cost of Used Fc – Total Cost of Base Case | Percentages of Reduction and Increase in Total Cost |
|---------------------------|------------------------------|-------------------------------------------------|-----------------------------------------------------|
| C30                       | 69,594.62                    | 13,373.5                                        | 24%                                                 |
| C40 (Base Case)           | 56,221.1                     | 0                                               | 0%                                                  |
| C50                       | 47,249                       | −8972.13                                        | −16%                                                |
| C60                       | 43,790.3                     | −12,430.8                                       | −22%                                                |
| C70                       | 37,635.5                     | −18,585.6                                       | −33%                                                |

C30 indicates a cost increase of 24% compared to the base case. This means that utilizing the C30 mixture would result in a 24% higher cost compared to the base concrete mix. C50 shows a cost reduction of 16% compared to the base case. Using the C50 mixture

would lead to a 16% cost decrease in comparison to the base concrete mix. C60 displays a cost reduction of 22% in contrast to the base case. Employing the C60 mixture would result in a 22% reduced cost relative to the base concrete mix. C70 demonstrates the most significant cost reduction among the mixtures, showing a 33% decrease compared to the base case. Utilizing the C70 mixture would lead to a 33% cost reduction compared to the base concrete mix. These percentages showcase how each concrete mixture's cost varies concerning the baseline concrete mix (C40) in terms of higher or lower expenses.

### 3.4. Percentage of Reduction and Increase in Total EC and Cost

The analysis in Figure 13 illustrates percentage changes in both cost and environmental impact concerning various concrete mixtures relative to the base case. The findings indicate that the C70 mixture shows optimal results, with a 33% cost reduction and a 27% decrease in environmental impact compared to the base case. Conversely, the C30 mixture exhibits a 24% cost increase and a 20% rise in environmental impact, making it the least favorable among the considered mixtures.



**Figure 13.** Summary of percentages of total reduction and increase in cost.

These variations in environmental impact and cost are attributed to the composition of materials, particularly cement. As cement proportions increase, emission coefficients rise,

leading to increased environmental impact. Conversely, higher proportions of the mixture reduce concrete and steel quantities, hence lowering costs for the same mixture.

Regarding high-resistance concrete like C70 or C60, several advantages include significantly higher compressive strength, increased elasticity standards, reduced concrete sections lowering structure weight, and enhanced durability against erosion and chemicals. However, its application has been limited to specific domains like tall buildings, bridges, and marine installations due to its traditional use focused on reducing section area and structural size.

Considering the quantities of concrete and steel required for the designated work area in this study, the C50 mixture emerges as a preferred choice due to its structural compatibility and lower environmental impact compared to the basic C40 mixture. The decision to focus on concrete with a compressive strength of 40 MPa and higher in this study was purposeful and in keeping with the project's unique setting. It is recognized that, in actual projects, designers frequently choose conventional compressive strength concrete, and this observation is well-justified [70]. The apparent disparity between this study's recommendation of higher compressive strength to align with sustainability aims and the widespread usage of 50 MPa (selected choice) concrete in actual projects can be explained by the multidimensional nature of construction decision-making. Practical projects frequently entail a variety of issues, such as structural needs, financial concerns, and local building standards [39]. Garcez et al. performed the life cycle assessment for C25, C50, or C75 concrete and found similar statistical results [5].

This recommendation factors in the carbon embodied in these materials, emphasizing the selection of an optimal mixture aligned with structural systems to reduce the environmental impact while maintaining structural integrity.

#### 4. Conclusions and Future Study

This study introduced innovative approaches like life cycle assessment (LCA) and embodied carbon (EC) assessments to hotel and building construction in KSA. It emphasized the role of material selection in mitigating carbon emissions during production, underscoring the importance of considering both environmental impact and cost in construction projects. Future work may explore further innovations in material selection to enhance the environmental and cost efficiency of construction projects in the KSA.

1. The C70 mixture demonstrated superior performance, showing a 33% cost reduction and a 27% decrease in environmental impact compared to the base case.
2. In contrast, the C30 mixture exhibited a 24% cost increase and a 20% rise in environmental impact, making it the least favorable among the considered mixtures.
3. Variations in environmental impact and cost were primarily attributed to material composition, especially the proportion of cement. Higher cement proportions increased emission coefficients, leading to an elevated environmental impact.
4. High-resistance concrete (e.g., C70 or C60) offers advantages such as significantly higher compressive strength, increased elasticity standards, reduced concrete sections, and enhanced durability, albeit with limited application to specific domains.
5. Considering concrete and steel quantities for the designated work area, the C50 mixture emerged as a preferred choice due to its structural compatibility and lower environmental impact compared to the basic C40 mixture.

Lastly, notations in this study about economic consideration in the form of cost calculations often concentrate on immediate expenses without taking into consideration long-term environmental repercussions like carbon emissions or resource depletion. However, this change will be considered for future studies.

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draft, M.W.A.M.; Writing—review & editing, M.S.M.A.; Visualization, M.S.M.A. and M.W.A.M.; Supervision, M.S.M.A. All authors have read and agreed to the published version of the manuscript.

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