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SUSTAINABILITY ASSESSMENT OF USING GREEN
CONCRETE MATERIALS FOR RESIDENTIAL BUILDINGS IN
EGYPT

Thesis for the Degree of Doctor of Philosophy (PhD)
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DOCTORAL COUNCIL OF NATURAL SCIENCES AND INFORMATION
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DEBRECEN, 2024

Hereby I declare that I prepared this thesis for the Doctoral Council of Natural Sciences and Information Technology, Doctoral School of Earth Sciences, University of Debrecen in order to obtain a PhD Degree in Natural Sciences/Informatics at Debrecen University.

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I also declare that the results published in the thesis are not reported in any other theses.

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**Sustainability Assessment of Using Green Concrete Materials for
Residential Buildings in Egypt.**

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TABLE OF CONTENTS

1 INTRODUCTION	10
1.1. Research Background	10
1.2 Objectives	13
1.3 Research Questions	14
1.4 Research Significance	15
2 LITERATURE REVIEW	16
2.1 The Construction and Residential Buildings Industries	16
2.1.1. Global Perspective for Using Sustainable Construction Materials.....	16
2.1.2. The Egyptian Residential Building Sector	18
2.2. Concrete and Green Concrete.....	20
2.2.1. Conventional Concrete	20
2.2.2. Cement.....	20
2.2.3 Green Concrete Material (GCM).....	21
2.2.3.1. Recycled Aggregate Concrete (RAC)	22
2.2.3.2. Supplementary Cementitious Materials (SCMs).....	25
2.2.3.3. Fly Ash Concrete (FA)	25
2.3. Sustainable Strategies and Green Concrete Materials	27
2.3.1. Circular Economy Principles for Using Green Concrete Materials	27
2.3.1.1. Applied Circular Economy in the Early Construction Process Phase.....	28
2.4 System Dynamics for Circular Economy Transition.....	29
2.5.1. The Sustainable Construction Materials.....	31
2.5.1.1. Green Building Materials and Sustainable Development Goals.....	32
2.5.2. Assessing the Sustainability Performance for Realizing Sustainable Development Goals SDGs.....	34
2.5.3. Residential Buildings Sustainability Features.....	36
3. MATERIALS AND METHODS.....	38
3.1. Identify GCM Strategies and Types for the Residential Building Sector	38
3.1.1. GCM Specifications and Standards for Residential Buildings.....	40
3.1.2. Proposing GCM Sustainability Conceptual Indicators Framework.....	41
3.2. Case Studies.....	41
3.2.1. Early Design Stage Case Study I	41
3.2.1.1. Building Data and Information	41
3.2.1.2. Classify and Quantify the GCM	41
3.2.1.3. Identify Concrete Materials	41
3.2.1.4. Compare Concrete Materials for Original and Modified Buildings	41
3.2.2. Construction Process Stage, Case Study II.....	43
3.2.2.1 Building Data and Information.....	44
3.2.2.2. Classify and Quantify the GCM	44

3.2.2.3. Quantify the Concrete Materials	44
3.2.2.4 Developing the Simulation Model for Optimum Scenarios	44
3.3. Developing a Sustainability Framework	46
3.3.1 Define the GCM Sustainability Indicators in the Residential Sector	46
3.3.1.1. Selection criteria for GCM-SI list	47
3.3.2. Determine the Contribution.....	48
3.3.3. Develop the GCM Sustainability Framework (GCM-SF).....	48
3.3.4. Analyzed the sustainability framework.....	48
3.4. The methodology limitations.....	51
3.5. Area of Study	53
3.5.1. New Egyptian Cities.....	53
3.5.1.1. New Borg El Arab City.....	54
3.5.1.2. New Cairo City.....	55
4 RESULTS AND DISCUSSION	58
4.1. Investigation of Egyptian Residential Buildings.....	58
4.1.1. Description of Egyptian Residential Building Types.....	58
4.2. Case study I	60
4.2.1. The Building Data and Information	60
4.2.2. Original and Modified Building	61
4.2.2.1. The Role of Design for Applying GCM.....	62
4.2.2.2. Modifying and Original Building Design.....	63
4.2.3. Classifying The Concrete Materials	64
4.2.3.1. Concrete Materials' Quantities for Specific Building Parts.....	64
4.2.3.2. Concrete Materials for Selected Building Parts	66
4.2.4. The Selection of the Most Optimum Building Scenario	66
4.2.4.1. The Steps for Reducing Cement Material	66
4.2.4.2. Comparison Analysis of CCM and GCM.....	68
4.2.4.3. Cement Production and CO2 Emissions	69
4.2.4.4. The Most Benefits of Using GCM	70
4.2.4.5. Sustainable Building Model.....	72
4.3 Case Study II	74
4.3.1. Building Location and Map.....	74
4.3.2 Building Data and Information Case Study II.....	74
4.3.3. Case Study II Building Drawing	75
4.3.4. GCM Classification for Case Study II.....	77
4.3.4.1 Modeling of the GCM Parameters	80
4.3.5. Model Development.....	80
4.3.5.1. The GCM for Achieve CE Principles	80
4.3.5.2. The Description of Different and Constant Variables Values of GCM Scenarios	81

4.3.5.3.The Conceptual Framework for Achieving GCMs Circularity Performance	82
4.3.6.The Causal Loop Diagram (CLD)	82
4.3.7. The Stock and Flow Diagram (SF).....	85
4.3.7.1 Model Boundary and Key Variable	86
4.3.8 System Dynamic Model	90
4.3.8.1. The GCM Simulation Process	90
4.3.8.2. The Cement Consumption for Different Concrete Types Scenarios.....	90
4.3.8.3. Natural Aggregate (NA) and Recyclable Materials.....	91
4.3.8.4. The CO ₂ Emissions for Different Concrete Types.....	93
4.3.8.5. The Construction Waste Reduction Amount Different Concrete Types.....	93
4.3.8.6. The Cost-Effectiveness of Different Concrete Types	94
4.3.9. Concrete Scenarios Analysis	95
4.3.9.1 The Effects of Using GCM for Achieving CE	95
4.3.10 The Circularity and Sustainability Performance ofGCMs Optimum Scenarios.....	98
4.4.Green Concrete Materials Sustainability Framework.....	100
4.4.1.The Residential Building Construction Features for Using GCM.....	100
4.4.2. Green Concrete Materials (GCM) Strategies and Types for Residential lding.....	102
4.4.3.The Relation Between the GCM and the Three Sustainability Pillars.....	102
4.4.4. The GCM- SI for achieving SDGs.....	104
4.4.5. Green Concrete Material Sustainability Indicators (GCM-SI) for Achieving Sustainable Development Goals SDGs.....	105
4.4.6. The Sustainability Framework for GCM-SI Contribution to the Pillars and SDGs.....	105
4.4.7. The GCM-SI High Contribution.....	106
4.4.8. The GVM-SI Low Contribution	106
4.4.9. The most GCM-SI contributed to achieving SDGs.....	107
4.4.10. Green Concrete Materials Sustainability Framework (GCM- SF)	109
5. CONCLUSION	111
6. RECOMMENDATIONS	114
6.1 The Study's Impact on Future Directions.....	114
6.2 Suggestions of Future Research	115
7. SUMMARY	116
7.1 New Scientific Achievements	118
REFERENCES	119
APPENDIX	142

LIST OF ABBREVIATIONS

Abbreviations	Meaning
GCM	Green concrete material.
GCM-SI	Green concrete material -sustainability indicators.
GC-SF	Green Concrete Sustainability Framework.
RAC	Recycled Aggregate Concrete.
SDGs	Sustainable Development Goals.
OPC	Ordinary Portland Cement.
GHG	Greenhouse Gas.
PCC	Portland Cement Concrete.
OPC	Ordinary Portland Cement.
SCMs	Supplementary Cementitious Materials.
FA	Fly ash.
CDW	Construction And Demolition Waste.
RA	Recycled Aggregates.
CCM	Conventional Concrete Material.
RAC	Recycled Aggregate Concrete.
RCA	Recycled Concrete Aggregates.
NCA	Natural Coarse Aggregates.
NA	Natural Aggregate.
CE	Circular Economy.
SD-BF	System Dynamic-Based Framework.
SD	System Dynamics.
LEED	Leadership in Energy and Environmental Design.
BREEAM	Building Research Establishment Environmental Assessment Method.
GPRS	Green Pyramids Rating System.
CLD	Causal Loop Diagram.
SF	Stock and Flow Diagram.
GGBS	Ground Granulated Blast Furnace Slag.

1. INTRODUCTION

1.1. Research Background

Rapid population growth is associated with a high construction activity rate that increases the number of residential buildings worldwide. The United Nations Habitat (UNH) reported that about 40% of the world's population is expected to live in residential buildings by 2030 [1]. In 2022, the new housing number reached 96,000 units per day globally to meet the demand for the nation's urbanization. Consequently, this resulted in an exponential increase in construction activities, particularly in the residential sector [85],[2],[3]. The construction industry is strongly responsible for achieving sustainability in three bottom pillars: economic, social, and environmental [4],[3]. At the same time, the sector is a significant contributor to economic growth, such as participating (5–10) % of employment rate and creating (5–15) % GDP (UNEP, 2018). On the contrary, building sector construction is a primary consumer of non-renewable energy and natural resources. Furthermore, it causes approximately 40% of energy consumed, 12% and 16% of water and freshwater use, and about 30% of greenhouse gas emissions worldwide, as well as solid waste generation [1],[2],[5],[6].

Countries rely heavily on concrete to support their urbanization needs for socio-economic growth, particularly in countries experiencing rapid population growth and fast urbanization [3]. Therefore, concrete and cement are the most common and widely used man-made materials and have become the second-fastest growing industry worldwide [7]. From an environmental perspective, the negative impact of using conventional concrete materials (CCM) will lead to natural resource depletion and release vast amounts of negative environmental impacts that are expected to continue for the next decades [8]. Conversely, concrete is considered an essential building material with several advantages, such as strength, durability, workability, and cost, and the most concrete type used is Portland cement concrete (PCC), which has a high production rate, reaching about six billion tons globally [7],[9]. Demand for concrete has increased due to its versatility in many structural applications, resulting in significant growth in the cement industry, particularly in producing Ordinary Portland Cement (OPC). Consequently, this growth has harmful effects, resulting in high energy loads and CO₂ emissions [10],[11]. The production of OPC demands a substantial amount of energy as the materials, such as calcareous and argillaceous substances, must

be melted at high temperatures of up to 1700°C. Furthermore, the chemical reaction that decomposes limestone (CaCO_3) into ($\text{CaO} + \text{CO}_2$) significantly contributes to a large carbon footprint. For each 1 ton of cement produced, approximately 0.9 tons of carbon footprint is generated, leading to an estimated global carbon footprint of 21.6 billion tons [12],[13]. According to the (World Energy Outlook 2016), cement production has about 8% of the total anthropogenic carbon footprint (The International Energy Agency) [8],[9],[14]. According to the global carbon budget 2023, the data of the CO_2 on territorial emissions in millions of tons in 2022, as well as the world cement production from 2015 to 2022 per billion metric tons, are shown in Figure 1, which reached 4.1 by the year 2022.

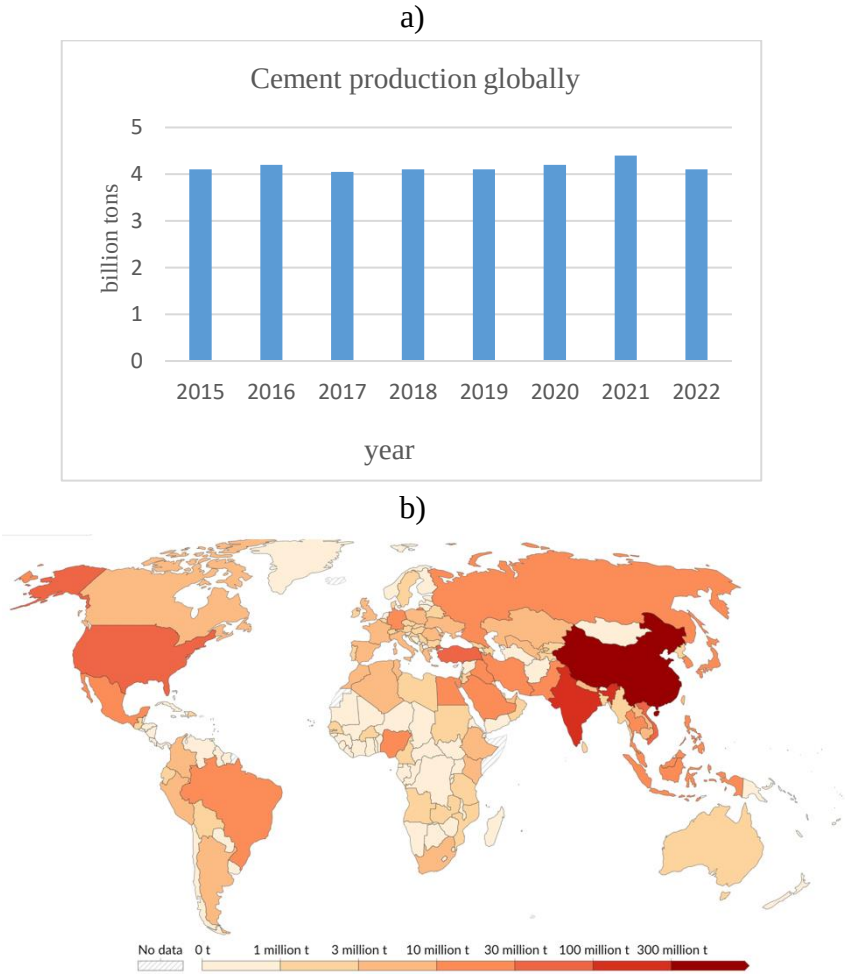


Figure 1. a) The cement production globally in billion tons, and b) the global annual CO_2 from the cement industry, which is measured in millions of tons [15],[16], Global Carbon Budget (2023).

Nowadays, increasing the priority for using sustainable construction materials with low environmental impacts and cost-effectiveness is highly recommended. At the same time, the continuous consumption of natural resources may prevent sustainability in the future [15]. Therefore, using GCM for future residential building projects to meet the needs of the nation's urbanization while reducing the construction industry's environmental burdens became crucial [17]. Whereas GCMs refer to concrete that contains recycled materials or has a low environmental impact in its production process. GCMs are essential for reducing the negative environmental impact and play a vital role in the building's life cycle. It can incorporate innovative technology and eco-friendly materials [18],[13],[19].

The GCM, in which the OPC is partially replaced with various supplementary cementitious materials (SCMs), like fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume, can reduce the environmental impact. For example, integrating the two types can reduce CO₂ emissions by 60%, incorporating 70% of FA and GGBS. Similarly, alkali-activated concretes reduce the GHG by approximately 70–75% [52]. While high-performance concrete can enhance durability and strength when compared to OPC concrete [20],[21]. Therefore, reusing recycled industrial wastes as a substitution for cementitious materials is considered an effective tool for cement reduction. This can help with environmental protection, such as energy savings, raw materials conservation, eliminating CO₂ emissions, and reducing waste generation even from industry or municipality waste, like construction and demolition waste (CDW) from construction activities [22],[23],[11].

Recently, the using of GCM in the residential sector has shown promising solutions as an alternative green material of CCM, and by using effective designs and techniques from the early project stages, which can achieve environmentally friendly and sustainable construction solutions [8],[24],[4],[25]. Furthermore, selecting the right GCM suitable for residential buildings is crucial for achieving several sustainability strategies, such as the circular economy (CE) and realizing the sustainable development goals (SDGs) [26]. For instance, using GCM is vital in eliminating waste generation based on reducing, recycling, and reusing strategies (WGBC, 2016). Most of the previous GCM research efforts mainly focused on GCMs' strength and durability. Still, the influences of sustainability dimensions for using GCM in the Egyptian residential building sector need more investigation [25],[27].

Meanwhile, the residential buildings sector plays a tremendous role in achieving sustainability, essential for ensuring the urban quality of life for people worldwide. Consequently, the sector can reduce natural resource consumption and energy use, which will lead to a decrease in emissions by 50% to reach the Paris Agreement climate goals in 2030 [1],[2],[4],[28]. Furthermore, it enables stakeholders to meet the development needs without realizing the environmental load throughout the building lifecycle [29],[30].

The lack of environmentally conscious buildings in the construction industry regarding the role of GCM resulted in a variance in stakeholders' understanding of the GCM concept. This raises questions about whether implementing GCM can achieve sustainability and what opportunities and obstacles exist when utilizing materials in the residential sector. Furthermore, sustainable construction materials procurement should be considered to meet the needs of present construction activities without compromising the future scarcity of natural resources and decreasing the negative impacts of residential building projects. Therefore, this dissertation investigates the role of using GCM to realize sustainability and seeks insight into the drivers and challenges of selecting and using GCM by developing a sustainability framework based on evidence-based solutions and eco-friendly methods for the Egyptian residential sector to bridge the gap between industrial and academic realms.

1.2 Objectives

This dissertation aims to assess the sustainability performance of using GCM and investigate the effects of using and selecting the GCM on natural resource consumption, CO₂ emissions, waste generation, and cost-effectiveness, based on CE core principles, SDGs, and three sustainability pillars in the design and construction phases of residential building projects in Egypt, in this regard the following steps will be considered:

- First, the GCM sustainability indicators (GCM-SI) will be identified by proposing a conceptual framework based on the primary data collected from the real and existing Egyptian residential building case studies. Additionally, secondary data was collected through the literature review, concrete codes and standards, green rating systems, and Egyptian residential building case study regulations

- Second, the effects of using GCM in the context of resource efficiency will be investigated based on concrete scenarios from the building case study I in the early design stage.
- Third, quantify and identify the parameters that influence the use of GCM to achieve CE by investigating the circularity transition for several GCM scenarios during the construction phase of a residential project based on case study II.
- Fourth, the simulation model will be created to select GCM' circularity performance for future use in residential projects.
- Fifth, developing a GCM sustainability framework (GCM-SF), integrating sustainability pillars and SDGs as a governing context for evaluating and enhancing the use of GCM in the RB sector. Finally, the contribution of using GCM and its opportunities and challenges to realizing sustainability will be evaluated.

1.3 Research Questions

To achieve that, the research attempts to answer the following:

1. What are the sustainability indicators for using GCM in the Egyptian residential building sector?
2. What are the effects of using GCM instead of CCM on cement consumption, natural aggregate, and CO₂ emissions in the design phase of residential projects?
3. How can several hypothetical concrete scenarios enhance the selection of GCMs during the construction phase?
 - a) How can system dynamic modeling (SDM) improve the selection of GCM to achieve a circular economy (CE)?
 - b) What are the sustainability criteria keys and indicators for using GCM in residential buildings?
4. How can GCM realize sustainability in future residential buildings?
 - a) What are GCM's contributions to achieving SDGs?
 - b) How can the GCM-SF participate in assessing sustainability in the design and construction phases?

1.4 Research Significance

The current dissertation is considered the first attempt to develop an assessment framework for investigating GCM's sustainability performance in Egyptian residential building projects in the design and construction phases. Furthermore, the novelty of using an eco-friendly approach based on the design-based solutions and system dynamic-based framework for developing the sustainable and SD simulation model presents the first sustainable GCM model for residential buildings, which promotes flexibility for comparing and using different GCM types and strategies. Investigating real case studies provides strong evidence and opportunities for future implementation. Additionally, the GCM-SF provides a call of action for environmental scientists, regional developers, researchers, and construction industry stakeholders, such as (engineers, architects, material manufacturers), and policymakers, to utilize the materials in future residential projects.

Meanwhile, developing a holistic sustainability approach based on the integration of the global common sustainability perspectives, such as CE, three pillars, and SDGs, promotes a wide investigation of the obstacles facing GCM's sustainability analysis. Furthermore, the importance of flexibility in promoting international-level implementation after modifying the local code, standards, and building regulations will open the door for more future investigations and research efforts. This will improve the use of the GCM in future residential projects by the following:

- Provide a sustainability indicators framework that assesses and analyses the use of the GCM for residential buildings.
- Integrating the global sustainable strategies, such as (CE, SDGs, and Pillars) and explaining the GCM contributions for applying sustainability.
- Investigating the inner variables and the complex system interrelations of GCMs selection in the design and construction phases.
- Promote sustainability assessment framework by integrating the indicators framework and case studies to analyze and evaluate sustainability performance based on quantification and qualification considerations.
- Increase sustainability practices by using GCMs for the residential building sector at local and international levels.
- Enhance future research by opening the door for more investigation for other building typologies with different and various GCM types and strategies.

2 LITERATURE REVIEW

2.1 The Construction and Residential Buildings Industries

The rapid population growth and urbanization resulted in an increasing number of new residential buildings and a high rate of construction materials consumption worldwide [1]. Natural resources such as water and aggregate used in cement and concrete production are considered the most essential and common construction materials used in the building sector. Consequently, the continuous consumption of natural resources causes a supply shortage and prevents sustainability in the future [15]. On the one hand, the United Nations Habits estimates that three billion people of the world's population expect to live in housing by 2030, which resulted in an increase in residential building numbers by 96.000 units per day globally [1]. This increases the average house floor area, massive materials, energy consumption, CO₂ emissions, and waste generation. Meanwhile, the construction of new buildings caused more than 50% of embodied carbon emissions by using six construction materials only, for example, concrete and steel, which were responsible for approximately 70% of these emissions [23],[31]. Since the building industry was caused by (38% and 14 GT) of energy-related greenhouse gas (GHG) emissions, it additionally consumed 16% of freshwater [32].

Despite all the previous global decarbonization, the construction industry can reduce emissions by approximately 50% by 2030, still considering the sector one of the three critical sectors that can achieve circularity and realize sustainability [28].

2.1.1. Global Perspective for Using Sustainable Construction Materials

In Europe, the construction industry is the largest employer, reaching about 20 million jobs in 2019, according to (The Concrete Initiative, 2019). Therefore, applying sustainable construction materials in European countries influences the final energy consumption and GHG emissions and reduces the extraction of raw materials by 42%, 35%, and 50%, respectively, by 2050. Additionally, the reduction of water consumption will be enhanced by 30% in the next few decades based on the roadmap for resource efficiency in Europe [33],[2],[34],[35],[36]. For instance, the investigation of the environmental impact and the addressing of sustainable new building strategies have been applied in several European countries.

In Sweden, new and innovative sustainable building codes are considered to improve the building lifecycle in terms of emissions and energy. Implementing environmental certifications to regulate and revise the CO₂ levels during the construction process of residential buildings.

Meanwhile, Switzerland applied a CO₂ emissions cap for the new and existing buildings and supported sustainable building systems, which are concerned with using sustainable materials and building insulation systems to reduce fossil fuel consumption [37],[38].

In Germany, the government established new measures for emissions reduction and parameters to meet the UN Agenda 2030 goals and targets. Increasing energy efficiency efforts for most densely residential building areas, by applying additional measures, such as tax relief for resources and energy-efficient renovation of old buildings [36],[37]

In the same regard, Canada applied the Green Building Code, which seeks to achieve high-performance, sustainable buildings with innovative technologies and sustainable construction practices, as a net-zero-energy-building code to reduce emissions and achieve a CE that can enhance climate resilience and recommends adopting by 2030 in most provinces and territories [34].

In the same point of view in Japan, applying the net-zero for residential buildings, in accordance with reaching zero energy consumption by the end of the current century. Especially for new residential projects, considering the building lifecycle from the production of the construction materials until renovation, dismantling, reuse, demolition, and disposal to landfill.

In the same regard 2018, in Latin America and Africa, the buildings & construction industry's final energy and CO₂ emissions accounted for approximately (24% of 21%), and (61% and 32%), respectively. Meanwhile, China, & India accounted for the regional energy and CO₂ emissions, about 27% of 24% respectively, and all the previous without accounting for the building materials manufacturing [2],[36],[39]. Approximately 450 km² of residential floor space in China was added to the market due to extensive urban development and excessive expansion by 2018 [40]. Therefore, raw construction materials are consumed severely, resulting in illegal sand mining to cover the high demands nationwide [41]. Furthermore, the massive extraction rate threatens the richness of biodiversity; for instance, the world's largest sand mining operation in Poyang Lake, in China, reached approximately 236 million m³ of sand between 2005 and 2006 [42].

In the same context, in Vietnam, the domestic demand for natural aggregate as a construction material, such as sand and gravel, has exceeded the country's limit, affecting the biodiversity and ecosystems of the country's rivers, lakes, and ocean. Furthermore, the high demand for fine aggregate has led to massive illegal sand mining in the industry. India's southwestern coast also has massive and indiscriminate sand mining, damaging floodplain areas and river basins [43].

2.1.2. The Egyptian Residential Building Sector

Egypt, one of the Middle East North Africa (MENA) region countries, is concerned with an urbanization strategy to improve natural resources and energy consumption and apply sustainability. The Egyptian construction sector is considered one of the crucial sectors for national economic growth and has several relationships with other sectors, future plans, and social and economic activities [44]. Nowadays, the sustainable practices inside the sector have witnessed interest from the stakeholders and construction experts due to the increasing consumption rate of construction materials in residential building projects. Meanwhile, residential buildings are the most common proportion of the total building stock, which accounts for approximately 83.2% of the different building typologies. This has reached about 13.5 million units in 16.2 million buildings [45].

Therefore, the sector is one of the highest energy and building materials consumers. Based on the 2020/2021 Electricity Holding Company report, the residential sector's electricity consumption accounted for 40.5%, compared with commercial buildings, which recorded 13%. Furthermore, concrete materials consumption will increase, resulting in increasing energy consumption, CO₂ emissions, natural aggregate, and waste generation streams, and it is expected to increase in the near future [46].

Meanwhile, the residential sector plays an important role in the national strategy for economic growth, which is considered one of the dynamic sectors and has gained tremendous attention from the private and public sectors. For example, the percentage of housing units implemented by the private sector reached 92.6% in 2021/2022, respectively, based on the Central Agency for Public Mobilization and Statistics [47]. However, the GDP growth contributed to an increase from 6.3% to 6.8% for the years (2018–2019) & (2020–2021), respectively, for the construction sector [44]. Accordingly, the Egyptian

government's economic reform strategy, established in 2016, paid more attention to the construction sector to meet market needs for new residential buildings as a solution for facing the challenges of population growth, improving the urban quality of life, additionally achieving sustainable development, and Egypt Vision 2030 (HBRC Arabic, 2023),[48]. Consequently, the country's investment in the sector reached approximately 865 billion (LE) Egyptian pounds between 2016 and 2022, approximately 173 billion LE, as shown in Figure 2.

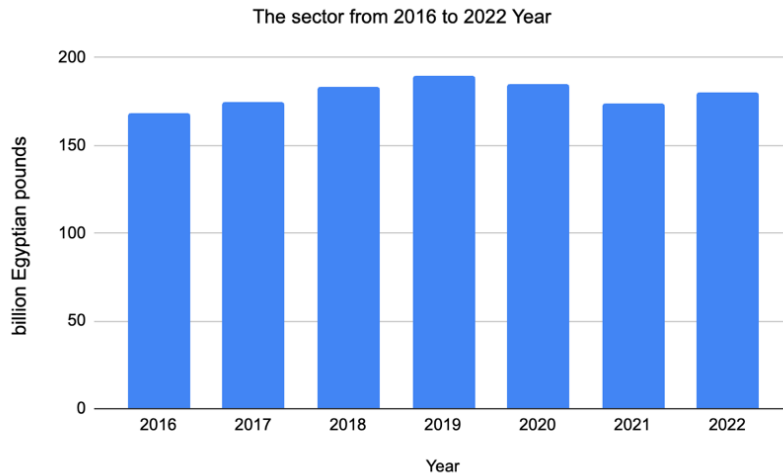


Figure 2. The sector investment from 2016 to 2022 [47].

However, the government reform strategy is concerned with increasing the urbanization rate across the country and integrating development initiatives. The new residential building rules, regulations, and codes are concerned with using sustainable materials and applying energy standards. Still, the lack of awareness of sustainable practices that led to using conventional materials highlighted the necessity for new legislation supported by empirical studies [38]. For instance, many raw materials are available in Egypt; still, the sector will severely consume concrete and cement materials through increasing national projects and establishing new cities nationwide. Therefore, more investigation is needed to assess the sustainability of using the GCM for the design and construction phases of Egyptian residential buildings to facilitate the transition to sustainable construction and achieve the sustainability dimensions.

2.2. Concrete and Green Concrete

2.2.1. Conventional Concrete

CCM is considered the most widely man-made construction material used; due to its availability and severe consumption, it is the most polluting construction material globally [49],[50],[15]. The PCC is the common concrete type used in residential buildings due to its ability and flexibility for site preparation, curing processes, and different characteristics and ingredients. Concrete comprises four main ingredients: water, Portland cement, aggregates, and air. It consists of two parts: aggregates and paste. Aggregates are fine and coarse, accounting for 60 to 80 percent of the concrete component. The paste comprises cement water and entrained air, usually accounting for 20% to 40% of the overall composite amount [51].

The global demand for construction materials exceeded 26.8 billion tons/year and is expected to continue increasing in the future [52]. For instance, in 2006, concrete production reached approximately 7.5 billion cubic meters per year, about one cubic meter per person globally. In 2020, the CCM volume reached 14.0 billion m³ globally, and the residential market contributed about 40% of total concrete consumption. Furthermore, the global cement and concrete market value reached about \$440 billion. Notably, by 2050, the world population is expected to reach 9.8 billion, and approximately 68% will live in cities [50],[53],[54]. Consequently, this will increase CO₂ emissions, dust, particulate matter, water pollution, primary energy use, and the depletion of non-renewable resources [51],[55],[56],[57].

2.2.2. Cement.

Cement is a concrete composite binder, accounting for 10-15% of the PCC volume. Global cement production reached 4.1 billion tons by 2022 and, due to increased demand, is expected to increase in the next decades worldwide [15],[50],[58]. In this regard, the annual CO₂ emissions in Egypt due to cement production reached 20.6 million tons in 2022. Thus, cement production is expected to increase by 40% by 2050 if there is no action taken for reduction measures. The contribution is about 7% of anthropogenic GHG emissions and approximately 8% of global CO₂ [14],[53]. One ton of cement causes 0.9 tons of carbon footprint in the atmosphere [59],[60],[61].

OPC is considered the third producer of CO₂ after fossil fuel consumption and land-use change based on energy consumption and cement production [12],[62],[63]. Global production has reached more than 4-fold since 1990, and 73% of global cement production is consumed in China [64],[65],[66]. The first step in cement production is the production of clinker, which involves heating carbonate limestone and CaCO₃ to produce oxides lime and CaO and release CO₂. Unfortunately, this process requires a huge amount of energy and CO₂. Additionally, a large amount of fossil fuels is used to generate significant heat to reach temperatures of over 1000°C, called "energy" emissions. This adds further to the problem, accounting for around 60% of emissions [12],[62],[66],[65].

Furthermore, it is responsible for over 70% of the construction industry's greenhouse gas emissions. Thus, the cement industry has grown rapidly due to the increasing demand for concrete materials worldwide [15],[35],[61]. Recommended that the industry reduce its direct emissions of greenhouse gases by at least 24% compared to current levels by 2050 to have a greater than 50% chance of keeping the global average temperature rise below 2°C. [67],[13]. Increasing the consumption of raw materials in concrete production, such as sand, water, and aggregates, is crucial for achieving sustainability in the construction industry.

Since GCMs are considered one of the most effective solutions for addressing these challenges, for example, supplementary cementitious materials (SCMs) can be used to reduce the total cement consumption and decrease the CO₂ emissions from the production process [49],[68]. This will be accrued with the collaboration between all decision-making parties, such as environmental scientists, developers, architects, engineers, concrete manufacturers, and the public and private construction sectors should be considered for further investigation [69],[70],[71],[5],[72],[73],[74],[75].

2.2.3 Green Concrete Material (GCM)

Sustainable concrete is an important starting point that promotes opportunities for sustainable practices when considering its use and selection from the early stage. It can also enhance residential projects' sustainability such as environmental, economic, and social aspects [24]. GCM is defined as concrete containing recycled materials in its components and/or having an environment-friendly manufacturing process while it's maintaining high

performance by incorporating innovative technology and eco-friendly materials. Using these materials for residential building types is crucial for reducing the negative environmental impact and plays a significant role in a building's life cycle [76],[77],[78],[79],[13].

GCM has received tremendous attention in recent decades due to its ability to play an essential role in reducing the negative environmental impact by substituting cement and NA with recyclable materials in the concrete mixture. This greatly contributes to achieving economic and environmental sustainability for construction activities [13],[80],[81],[82]. Notably, several scholars have suggested that optimizing the recycled materials used as alternative cementitious materials can improve the properties of GCM, such as strength, durability, workability, and fire resistance. Therefore, the substituting of concrete mixtures with different SCMs, like industrial and municipal wastes, can help in reducing the emissions of the CCMs component [83],[84],[85],[86],[71],[87].

For example, the use of FA, including calcareous and siliceous (ground granulated blast furnace slag (GGBFS) and silica fume (SF), is considered a viable choice for realizing sustainability [88]. Additionally, the substitute of recycling materials based on municipal waste, such as CDW, can reduce the NA of the CCMs portion and produce eco-friendly materials [88],[89],[90]. However, compressive strength is the most important parameter of GCMs. It depends on the ratio of the concrete component, cement type, source of aggregates, and their properties, which determine the concrete's behavior and function. Hence, the variety and availability of GCM types and strategies can reduce natural aggregate consumption, like RAC based on local recyclable materials can improve the final residential unit cost [91].

2.2.3.1. Recycled Aggregate Concrete (RAC)

Aggregates are considered the major component of concrete; 70% - 80% of OPC volume is sand and coarse aggregate, and the global demand for aggregates in the construction industry has been estimated at about 20 billion tons per annum [92],[93].

Consequently, this indicates that massive consumption will lead to significant energy use, depletion of natural resources, and global ecological degradation. In the same context, the production of RAC is affected by RCA in terms of their collection, classification, recycling, and transportation,

whereas the manufacturing process of RAs faces difficulties due to the transportation process from the demolition sites, which affects the final cost of concrete material, thereby the total project cost [94]. Moreover, the recycling process includes different stages such as classification, screening, eliminating pollutants, and removal of other construction materials such as steel, ceramic, brick, and wood to transform the concrete debris into different fragment sizes to produce high-quality RCA.

On the other side, rapid urbanization in Egypt resulted in generating a large number of CDWs from the demolition process and reconstruction of old residential buildings in many areas, which increased the opportunities for recycled materials availability and high-quality aggregate with different particle sizes for different durability ranges of GCM mix [26]. Therefore, using GCM can provide an eco-friendly solution, especially depending on reusing and utilizing the CDW, by using RCA production based on RAC that achieves environmental and economic benefits [87],[95],[96],[97].

Several studies have highlighted the necessity for careful consideration and evaluation of these materials and their important role in enhancing the durability of concrete materials, particularly GCMs, which contain RCA [98],[97],[98],[99],[100],[101].

However, defining the RAC physical properties faces challenges due to the significant regional differences in the RCA, which are shared in concrete components. Therefore, the quality of NCA can be enhanced after properly treating and controlling the particle size distribution to maintain the final concrete quality and compressive strength, which is associated with achieving cost-effectiveness [102],[103]. Meanwhile, shown that GCMs containing less than 50% mixed RCA do not experience significant changes in compressive or flexural strength [104],[105],[106]. Furthermore, the study by Azevedo et al. [100] evaluated recycling CDW in mortar production, investigating the properties of four different mortar mixtures after partial and complete substitution of natural fine aggregate. The results showed that using CDW enhanced the compaction degree and increased the compressive strength of the mortar.

In the same context, to meet the mortar's standards and requirements, replacing natural sand with CDW should not exceed 25% to avoid increasing water use, which is investigated by Colangelo et al. and Marvila et al. [99],[107]. In the same context, Al-Gahtani et al. [95] studied the sustainability benefits of using demolition and industrial waste as replacement

materials for aggregates and cement, respectively, to produce GCM. They used crushed demolition site waste, which contained concrete waste as fine and coarse aggregate. The study showed that using such demolition recycled materials as replacement materials did not significantly change their mechanical characteristics and enhanced the properties of GCM.

Al-Mansour et al. [97] also discussed using RCA in concrete mixes to replace NCA. They found a reduction in environmental impact and the cost of NA, as well as controlling the particle size distribution and keeping the balance between resistance and concrete compressive strength; the proper treatment should be applied to enhance the concrete quality. Furthermore, the substitution ratio of 25% to 100% by RCA reduced the mechanical strengths by 5% and 25%, respectively, recommending that it be suitable using the material for general works and moderate conditions. In the same regard, Tam et al. [102] discussed using CDW as recycled aggregates for infrastructure development, highlighting that it depends on their specification and quality. They suggested using RAC in construction projects could offer environmental and economic benefits by reducing CO₂ emissions and promoting civil engineering works, such as concrete pavements and roadways.

Meanwhile, El-Hawary et al. [108] examined the quality of recycled concrete and recycled aggregates as a complete replacement for natural coarse aggregates (NCA). They found that the mechanical properties of the concrete products increased in strength to 35 MPa, with a fixed 0.48 water-to-cement ratio for all concrete mixes. They also observed that reducing the mechanical strengths by 5% or 25% had no significant differences, recommending that the materials can be used for general practice purposes and moderate conditions. However, various GCM strategies improved the properties of RCA. They modified it for use in high-grade applications by increasing the quality of RA with integration with SCMs, such as curing RCA by carbonation to enhance the concrete properties and reduce its negative environmental impact rat.

Further investigation and development of the characteristics and applications of CDW in the residential building sector are needed [103],[109],[110],[111],[112]. Rahal K.[113] discussed the mechanical properties of RAC, which are made from old concrete structures demolished within the NAC, by comparing ten concrete mixes of RCA with different ranging strengths starting by 20 and reaching 50 MPa. The 28-day cube and cylinder, the compressive strength, and the indirect shear strength of RAC were an average of 90% of the NAC in the same mix proportions and played

a similar role. Additionally, the RAC modulus of elasticity is low by 3% between 25 and 30 MPa compressive strengths, compared with NAC, and the strain at peak stress in RAC is like NA.

2.2.3.2. Supplementary Cementitious Materials (SCMs)

However, the OPC in the cementitious concrete component is associated with the major CO₂ emissions concern; partially substituting cement with SCMs is considered an effective strategy for decreasing the cement production process's energy consumption and reducing waste generation and GHG emissions [114]. For example, 1-kilogram substitution by SCMs is estimated to reduce 1 kg CO₂, such as FA, ground granulated blast furnace slag (GGBFS), silica fume, and rice hush ask (RHA) [115]. For example, GGBS is a by-product of pig iron production and is used in different ratios in cement replacement to reach 50% by mass of total cementitious content. Furthermore, it can improve concrete workability and reduce thermal cracking by improving the concrete chloride resistance [110]. In the same regard, the SF is considered a by-product of the (silicon and ferrosilicon) industries and is used for high-performance and high-strength concrete with difficult environmental conditions [109],[116].

2.2.3.3. Fly Ash Concrete (FA)

FA is the most widely used SCM that is substituted at varying levels for cement and is considered a famous by-product material of the burning coal to generate electricity at power stations [117],[118]. Since coal is considered the main source of electricity worldwide, the massive amount of coal consumption resulted in a large quantity of FA, defined as “by-product materials from coal-based power stations resulting from coal combustion [118],[119]. Despite the increasing movement of replacing fossil fuels with renewable energy sources such as wind, solar, and biogas, increasing energy demand has caused a reliance on “coal-fired power plants” worldwide, which has increased FA uses in various fields [120].

For example, using FA in concrete as a partial cement substitution started in the late 20th century, which can improve the compressive strength and durability of the concrete [83],[85].

Furthermore, FA can improve workability and pumpability and enhance concrete resistance.

One of the advantages of FA has been researched to mitigate the waste disposal problem; additionally, reducing CO₂ emissions and energy consumption is considered a clean production solution [121]. Consequently, the partial substitution of OPC with FA reduced waste disposal and cement consumption, increasing concrete performance and supporting CE principles [84],[122].

On the one hand, using FA is considered a sustainable option because it closes the materials' loop by recycling waste materials and reusing them as new materials sources [123]. For instance, it can replace concrete 'cement by 20% to 60% in volumes of concrete materials, which is higher than the OPC in long-term strength, so it can be used in several structural engineering applications and is suitable for various applications [124]. Furthermore, it can improve natural resource consumption's concrete cost and efficiency at the local, regional, and global levels [88].

Therefore, using FA as a substitution material for concrete production has obstacles and challenges, such as slow pozzolanic reaction, dark gray color, varying its quality based on the source, increasing transportation costs, and unavailability in rural and suburban areas [123]. However, the slow pozzolanic reaction of the concrete containing a high FA proportion can increase compressive strength compared to the CCMs, which leads to high recommendations and is suitable for use in residential applications [125],[126]. Therefore, the selection of FA in this dissertation to investigate its role as a by-product waste material for producing GCM to achieve the following: (reducing waste generation, keeping resources in use for as long as possible, and maximizing their value). Which is considered a sustainable option and perfectly embodies the core sustainability performance and principles of GCMs. Furthermore, using these materials in residential applications, especially low-rise residential projects, allows opportunities for more experimental investigation of the partial substitution of FA concrete instead of CCMs [124].

2.3 Sustainable Strategies and Green Concrete Materials

2.3.1. Circular Economy Principles for Using Green Concrete Materials

The CE concept was applied based on regenerative and restorative methods when natural resources are used long-term to maximize their benefits. Additionally, it supports economic growth and environmental conservation by promoting (recycling, reducing, and reusing) strategies for waste materials and enhancing their performance (Ellen MacArthur Foundation, 2012), [127], [128]. CE strategy offers numerous economic benefits and opportunities, complements reducing carbon emissions, and promotes decarbonization in the cement and concrete industries, leading to a more sustainable and prosperous future scenario (Ellen Macarthur Foundation, 2019) [50],[129],[130]. Using GCMs has influenced the construction and concrete industries by selecting the optimum sustainable scenario to meet the resource efficiency and energy use criteria. Thereby, it is necessary for several scenarios to investigate and define suitable alternative materials for circularity drivers through the characteristics of the material's value and scarcity of natural resources [122]. Figure 3 shows the GCMs circularity principles for residential buildings, such as redesign for cement reduction, cost-effectiveness, reselecting the design for durability, replacing with alternative sustainable materials, remanufacturing or recycling the waste materials for producing new materials, reusing as a new source, and reducing the waste quantity for disposal to landfill during the building life cycle [131],[144],[134].

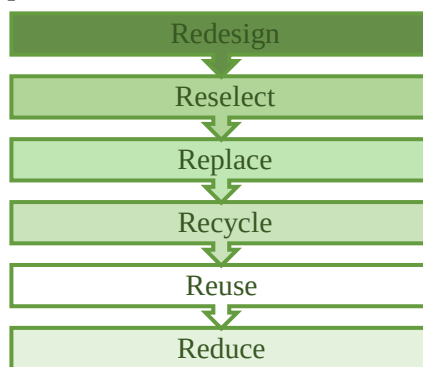


Figure 3. Circular economy principles for green concrete materials (GCMs), [24],[135],[136].

Therefore, the transition to CE in the construction process of residential buildings needs modifications to recognize the causality relationship between economic and ecological systems in concrete and cement usage [23],[128],[130].

Meanwhile, the CE seeks to apply resource extraction from waste materials [135],[137],[138],[139]. Therefore, operationalizing circularity in the construction process should be cross-disciplinary decision-making from the first project stage [134],[135]. Moreover, GCMs have excellent hardened properties, which lead to reduced maintenance and improved building lifespan, which is considered an indicator for achieving CE core principles by scoping innovation and developing new methods that can help improve the uses of recyclable materials instead of natural resources for the future residential projects [77],[78],[97],[142].

2.3.1.1. Applied Circular Economy in the Early Construction Process Phase

The challenges for applying CE in the construction process of residential buildings started from the first project stage, such as selecting the optimum concrete materials associated with improving the project quality, minimizing negative environmental impact, and reducing the total project cost [24],[136]. However, the construction process consists of five phases, starting with planning, design, pre-construction, procurement, construction, and followed by post-construction; therefore, starting from the initial phase, which consists of three steps (feasibility study – schematic design -contract documents), by managing the project challenges such as proper design, suitable materials procurement, and project management have an essential role in investigating and solving the obstacle of the complex issue [143],[144].

Therefore, investigating the causal change cycles between socioeconomic and natural systems should be accounted for by applying more clarification of CE principles to enable the construction and environmental stakeholders to consider a long-term strategy for selecting concrete materials [130],[145]. Despite the difficulties and obstacles the construction stakeholders face transitioning from a linear economy (LE), such as the massive consumption of concrete materials and the absence of a resource efficiency strategy [143]. Using simulation models to select the most optimal

materials that can be applied to CE promotes a new opportunity to address the challenges and interventions in the construction industry [134],[146].

Additionally, increasing the cooperation between the project team for materials and information needed leads to appropriate decisions and selection between different concrete types [147]. To facilitate cross-disciplinary and informed decision-making, adopting the GCMs selection perspective and predicting future scenarios should be investigated to fundamentally operationalize CE [128],[145],[144].

Therefore, the growing interest in simulation tools facilitates and clarifies the inner relations between the GCMs' parameters and investigates the positive and negative relations that can affect one parameter to another.

2.4 System Dynamics for Circular Economy Transition

SD has allowed the development of complex system models in recent decades. Several scholars proved that SD could be a vital tool for facilitating and identifying the CE complexity process by promoting models that can analyze complicated variables through simulation software. This would facilitate the investigation of the inner and interconnection variables and their feedback inside the complicated system [148].

SD was developed by Jay.W. Forrester in 1950 and was considered a simulation modeling technique that can represent the complex structure for the systems feedback loops of the materials and information based on stocks, fluxes, and auxiliary variables [149]. It helps manage the complexity in different fields by encouraging closed-loop thinking and comprehending the causal structures underlying behavior [149].

Using SD to investigate the selection of GCM promotes proactive system experimentation and gives more insights into policy and decision outcomes. For instance, (SD-based simulations) can be used for investigating the trends of CO₂ emission and predicting energy consumption in the urban context [150],[151],[152]. Furthermore, it can be used for regional planning, natural resources management, and environmental protection, enabling the stakeholders to investigate complex issues effectively. In the same context, the study [153] investigated integrating environmental assessment and management among various modeling approaches. Meanwhile, the SD applications investigated urban development through household structure and population.

Therefore, SD's ability to understand and examine quantitative and qualitative data during construction projects in the concrete and cement industries helps predict future challenges. The system dynamic model (SDM) is a policy tool for sustainable cement and concrete investigation [148],[152],[154]. For instance, the SDM was used to assess several CO₂ emissions policies in the Indian cement industry between (2001 and 2020), [155]. While the study by Ansari et al. [156] developed SD to estimate the future energy consumption and CO₂ emissions from 2005 to 2030, they analyzed the cement industry's CO₂ emissions and developed SDM with different scenarios.

Furthermore, Proaño et al. [157] investigated the economic evaluation of cement industry emissions. Furthermore, Ekinici et al. [158] discussed using SDM to assess the cement industry's environmental management in the streaming data. Notably, Pieroni et al. Pieroni et al. [159],[160] addressed using SD for the business model to apply CE transitions, a novel tool for decision-makers concerned with reducing uncertainties for managing dynamics and anticipating future scenarios. Therefore, for applying CE transitions in a complex system like the construction industry, which is dependent on linear practices and the massive use of natural resources, there is a necessary for more empirical studies were needed to bridge the gap between academic and industrial realms, as well as enhance sustainable practices.

2.5 The Green Concrete Materials for Residential Buildings' Sustainability Aspects

The history of the sustainable development concept refers to maintaining environmental quality [161]. Defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs,” this is called (our common future) and was established by the Brundtland Report, which characterized the sustainable development between the three pillars (environment, economy, and society), as shown in Figure 4, [162],[163].

However, the most common two global perspectives are sustainability's three pillars and the United Nations (UN) sustainable development goals (SDGs). Integrating the two perspectives will provide a valuable outlook on sustainability evaluation due to the increased implementation of sustainable

strategies between the environmentalists and construction stakeholders [75],[164]. Additionally, they have various paradigms and scopes, such as the pillars being widely concerned, while the SDGs have more defined goals and specific targets [165].

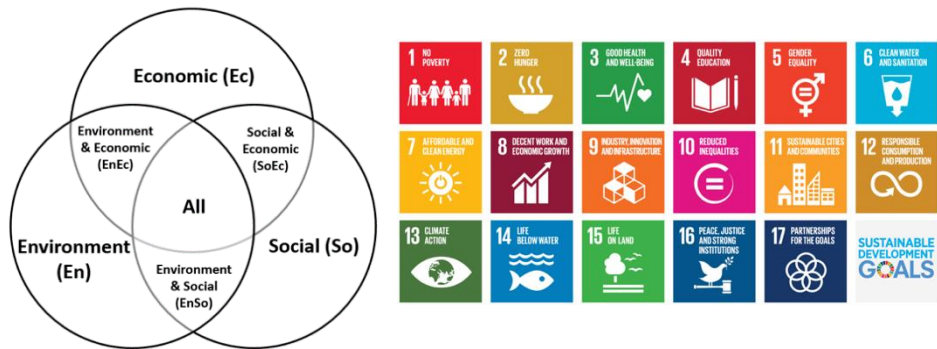


Figure 4. The three pillars of sustainability and the sustainable development goals adopted from the UN 2030 agenda [65],[154],[155].

However, assessing GCM sustainability is still unclear, and need for a comprehensive understanding of sustainability [143]. Therefore, investigating GCM sustainability requires applying sustainable development by integrating several eco-friendly strategies, which is essential for evaluating sustainability performance and using it as a valuable assessment tool for the future [136].

2.5.1. The Sustainable Construction Materials

Using sustainable construction materials for residential buildings, enhancing environmental protection, and promoting recycling, reusing, and reducing strategies are essential for realizing sustainability. Contrary to conventional construction materials, which consume severe natural resources, these materials lead to environmental burdens, which require urgent action from construction and environmental stakeholders' organizations. According to the World Green Building Council, increasing the suggestions for environmental scientists, engineers, and designers to use multidisciplinary approaches to integrate SDGs into residential building projects provides countless benefits for reducing economic and societal challenges, such as

improving human health [73]. Furthermore, international rating systems, such as Leadership in Energy and Environmental Design (LEED), focus on energy and water efficiency, which strongly contributes to SDGs [166],[167].

Therefore, selecting appropriate sustainable building materials, including recyclable materials such as industrial, agricultural, and municipal waste, which can reduce energy use, CO₂ emissions, and depletion of natural raw materials, and is considered a starting point for sustainable development [66],[65],[168],[5]. Furthermore, applying sustainability performance became crucial throughout the project's phases, from the design and construction process to operation and maintenance throughout a building's life span [167].

In this context, the study by Sánchez-Garrido et al. [72] is concerned with applying modern construction methods that enable eco-friendly materials to improve the economic benefits of conventional construction materials. Therefore, Goubran et al. and Goubran S. [75],[169] developed the two mapping tools to examine the sustainability in the design process of building projects by focusing on achieving the (SDG4, SDG6, SDG7, SDG9, SDG11, SDG15, and SDG17 from the SDGs. They investigated the relationship between the building design phase's direct and indirect impacts, which aligned with (SDG6, SDG7, SDG9, SDG17), and (SDG4, SDG8, SDG11, and SDG15), respectively. Moreover, analytical tools for integrating the design phase approaches based on the SDGs' vision are proposed. They found that 17% of the SDGs related directly to construction and 27% indirectly. They concluded that the construction activities are most important for achieving SDG11, SDG6, and SDG7. Additionally, Sánchez-Garrido et al. and Zastrow et al. [72],(Zastrow et al. 2017) analyzed the economic and environmental aspects from the design perspective and reflected that high-quality housing could be constructed without making it more expensive. Therefore, Agbesi et al.; Goubran [171], [75] focused on adopting sustainable practices of construction procurement materials to face the challenges of achieving SDGs in construction projects.

2.5.1.1. Green Building Materials and Sustainable Development Goals

In the context of investigating the role of green building materials in achieving SDGs. Wen et al. [172] proposed a mapping tool for quantifying the relationship between sustainable and green buildings and the SDGs, which validated it in a LEED-certified building as a case study. This resulted in

SDG3, SDG7, and SDG11; SDG12 were considered the most related goals; meanwhile, it was considered that target 7.3 was the intermediate pathway in the green building rating tools. However, they found that the contribution to SDG9, SDG13, and SDG15 was relatively small. Furthermore, the study by Secher et al. [173] suggested that the choice of green building materials has a significant direct and indirect effect on several goals, including ‘SDG3, SDG6, SDG7, SDG8, SDG9, SDG11, and SDG12. Similarly, Alawneh et al. [4] identified a strong relationship between energy and water efficiency and contributing to various SDGs, such as: [SDG6, SDG9, SDG12, SDG13, and SDG15]. They proposed an evaluation framework of the contribution of the previously mentioned SDGs during the building project life cycle. Moreover, Scrucca et al. [5] recommend sustainable practices and tools for implementing the SDGs, with the consideration of prioritizing certain goals.

In the same regard, the study by Omer et al. [174] developed a conceptual framework for the contribution of SDGs and building materials and found that selecting building materials is considered an important step to achieving SDGs, concluded the importance of creating a multi-criteria optimization tool to evaluate the material's efficiency in the early construction stage. They clarified how green buildings can play a significant role in achieving SDGs and found that nine of the SDGs, including “SDG3, SDG7, SDG8, SDG9, SDG11, SDG12, SDG13, SDG15, and SDG17” can contribute towards meeting sustainable development.

Since sustainable concrete materials were founded in the 2000s, the sector has taken steps towards sustainability to reduce negative impacts. These are considered eco-friendly materials that can be enhanced to contribute to the 2030 agenda established in 2015. The lack of a GCM's conceptual standards definition prevents its theoretical underpinnings from being detailed, which allows for various interpretations from different perspectives.

The study by Burgass et al. [175] discussed an understanding of the measurable systems that depend on category contributions in conceptualizing sustainable development. According to ISO 14040:2006, the life cycle assessment (LCA) is “the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.” Similarly, Anastasiou et al. [176] assessed and compared the GCM's environmental benefits by considering the LCA as a vital tool for assessing sustainability.

Meanwhile, Teh et al. [53] identified the GHG from geopolymer, concrete, and cement-based on LCA's four main stages in Australia. Also, Marinković et al. [177] identified and presented a comparative assessment for different GCM mixes with the same compressive strength and workability using LCA, considering the construction activities, transportation, and local materials in Serbia. The study proved that the alkali-activated FA concrete with natural aggregate NA and the high-volume FA with RAC had the best environmental performance, and the lowest performance was the RAC mix, which included cement binders.

Furthermore, the LCA applied by Borghi et al. [178] quantified and evaluated the energy use and CO₂ emissions related to the construction process in all the stages regarding material consumption, energy use, and environmental emissions. Additionally, Atmaca et al. [179] identified primary energy consumption and CO₂ emissions by building LCA in two residential buildings in Turkey. However, the construction activities for residential buildings generate a high value in the economic and environmental aspects, but these projects usually consume more material than their needs. Therefore, achieving the same mechanical durability and strength of concrete using RAC with low cement content in the building's structural works is possible.

In this regard, Guo et al. [180] identified the environmental impact and mechanical properties of RCA building blocks by using LCA. They showed that the RAC is considered to have less environmental impact than CCM and can play a crucial role during the building life cycle and enhance sustainable development. Meanwhile, Marey et al. 2022 [24] investigated the effects of using GCM in residential buildings in Egypt. The study identified the role of substituting the GCM performance in the early stage of construction processes and the reduction in carbon emissions by replacing the CCM with RAC for selected non-structural building parts after improving the original building design.

2.5.2. Assessing the Sustainability Performance for Realizing Sustainable Development Goals SDGs

According to the UN (Resolution 70/1-Transforming our world), the 2030 Agenda for Sustainable Development specifies the 17 SDGs and their 169 targets as a sustainable framework. Therefore, assessing the sustainability performance through construction activities becomes essential in improving

the sector. In this regard, Rajabi et al. [181] integrated the sustainability pillars with the SDGs agenda to implement at regional levels based on the stakeholders' national regulations and specific priorities. This identifies the sustainability keys and indicators for evaluating the execution phase sustainability performance. Additionally, Sharma et al. [182] identified and mapped the parameters for using the phase change materials on a large scale in concrete, and the study showed that a significant use promotes the potential for achieving (net-zero-ready buildings), during its lifespan and could contribute to SDG 7, SDG 11, and SDG 12 which is strongly related to realizing SDGs. Gettu et al. [94] proposed a framework for selecting the properties of the concrete mixture based on sustainability aspects; they depended on the two objective indices of energy intensity, integrated CO₂ emissions, and concrete durability parameters. A study by Opoku et al. 2022 [27] highlighted the importance of applying GCM to enhance infrastructure and biodiversity evaluation for achieving the 15 goals of the SDGs.

Furthermore, Panesar et al. [166] investigated optimizing material consumption and reducing carbon footprint. Meanwhile, Opon et al. [183] explained the sustainability of the concrete material indicators framework; the study focused on integrating the performance and operationalized sustainability indicators. They identified the indicator's causality and established the link between sustainability pillars and the SDGs, which helped select the most appropriate concrete sustainability indicators for evaluation.

However, the LCA was performed for the different binders, and by-product materials such as fly ash and slag were used as an OPC substitution. Conversely, the CDW is part of the GCM mixture and is considered an environmentally friendly manufacturing process for recycled concrete components. In this regard, Tam et al. [102] explored the possibility of utilizing CDW as recycled aggregates (RA) for infrastructure development. The RA specifications and quality define the CDW potential for RAC, which could offer substantial environmental advantages by decreasing CO₂ emissions and facilitating civil construction projects for roadways and pavement. As such, they strongly suggest implementing RA materials on a larger scale in construction initiatives.

Therefore, using RAC-based CDW is considered an example of GCM sustainability behavior. It reduces cement consumption and energy use by (50–75%) and results in reducing landfill disposal and CO₂ emissions by (10–30%), respectively [21],[107,184]. Using high technology and innovative

solutions are investigated by Alami et al. [185], which identified the role of using new technology, such as 3D concrete printing. The study demonstrated the three types of cementitious mixtures and found a cost reduction between 78% and 60% and a water reduction of approximately 20%. However, various studies have compared different building materials and positively reported that GCM is more environmentally friendly and has the same functionalities and properties as CCM regarding building life services were investigated by Al-Mansour et al.; Rahal K.; El-Hawary et al. [103],[108],[113]. At the same time, there is an absence of awareness of using GCM, which is still a new direction and needs more public and private sector practices and usage in the construction industry and more attention to the material's roles to achieve SDGs [165]. Additionally, it is necessary to identify the materials' social, economic, and ecological behaviors among the construction industry stakeholders. The cooperation for applying new rules and regulations considered attention from several parties, such as the policymakers, regional developers, engineers, architects, environmental scientists, builders, market suppliers, and consumers, for actively participating in driving SDGs [182],[186],[187].

Despite this, GCM is considered a sustainable and environmentally conscious choice and offers a range of benefits for the residential building industry, which will be investigated further in future research [72]. Many obstacles exist to using GCM in the residential building sector to achieve sustainability, such as skilled labor, supplies, safety conditions, and the absence of GCM's specific regulations. These lead to the necessity of assessing sustainability frameworks that can help public and private organizations develop new policies and technical standards.

2.5.3. Residential Buildings Sustainability Features

However, GCM is defined as a concrete material produced using eco-friendly materials and practices [71], [6], [7], [185], [186]. Concrete is widely employed in residential buildings for its numerous advantages, such as high durability, fire resistance, and energy efficiency, making it an optimal choice for residential construction projects. Meanwhile, residential buildings have a distinctive typology that diverges from other structures using concrete materials, often prioritizing aesthetics, occupant comfort, cost-effectiveness, and extending the building's life span. However, constructing low-rise

residential buildings requires smaller size, scale, and load requirements than other building types. Still, safety and well-being are needed to select the right concrete materials properly.

This resulted in increased use of GCM for different purposes, such as decorative walls and polished floors, which usually differ from other building types. Even though the concrete compressive strength for the residential buildings construction process, the quality of concrete used for finishing surfaces is often given more attention. Despite the environmental perspective that the rapid urbanization and construction activities of residential buildings have adversely affected the ecosystem and biodiversity. Despite recently increasing global recommendations for using GCM, it has garnered tremendous attention in the research agenda worldwide, and the necessity for sustainability evaluation to clarify the right actions that will contribute to realizing SDGs.

3 MATERIALS AND METHODS

Developing a sustainability framework for assessing GCM is considered a comprehensive process. Therefore, applying a suitable methodology to identify the research scope and limitations promotes the principles and procedures of the current dissertation. Eco-friendly assessment approaches are developed and used in various research stages to develop the sustainability framework by including theoretical and empirical methods. Therefore, several methodologies and strategies are introduced to evaluate the GCMs' sustainability performance usage for residential buildings in Egypt.

However, integrating primary and secondary data for GCM use in residential buildings is crucial for both the early design phase and the construction process. Providing a comprehensive understanding of GCMs where necessary for using a precise blend based on primary and secondary data. For example, primary data, such as concrete component quantities, building design, information, dimensions, measurements, classifying various concrete specimens, and several concrete scenarios incorporating varying proportions of RAC and FA for structural and non-structural building parts, provides empirical evidence on reducing the consumption of concrete of the same and equivalent mechanical properties and durability of the building. Simultaneously, the secondary data, like concrete codes and standards, residential building rules and regulations, and government reports, support the establishment of the benchmark for acceptable performance. Furthermore, by comparing the primary data against these secondary standards, the study can assess the suitability of GCM for specific applications. For example, using both alongside each research stage plays a vital role in identifying the local availability, labor cost, and concrete cost, which can inform the social and economic feasibility of using and selecting GCMs. Therefore, the integration approaches ensure that the research findings are both scientifically sound and practically relevant, promoting the adoption of GCM as a sustainable construction practice. Therefore, using qualitative and quantitative analyses, which include primary and secondary data working together as a complementary work, adds more accuracy to research findings, and the methodology consists of the following stage:

First, the theoretical part is applied based on the literature review of the previous research efforts for each research phase to cover all the investigation needs in the context of research goals. For example, it is applied to identify

sustainable construction, residential buildings, CE core principles, sustainability perspectives, green building rating systems, GCM types and strategies, and SDGs for creating and consolidating the GCM sustainability indicators framework. It will be discussed in detail in the next section. The importance for this step helps to understand the most important research efforts and recent findings.

Second, in the empirical studies based on real and existing residential building case studies, methods to investigate the following:

- The effects of using GCM by quantifying and weighing their consumption based on optimizing concrete materials through the early design stage by using a design-based solution method for applying GCM as alternative materials.
- The selection of GCM for achieving CE core principles uses system dynamic-based framework methods to select the most optimum scenario among various hypothetical scenarios in the construction process phase.
- Allow for the identification of the relation between the GCM variables during the construction process.

During the case studies process, information and data are gathered in various ways, including the official project documents, on-site measurements, Government reports for residential buildings rules and regulations, concrete codes, on-site observations, and in-depth discussions.

Third, the GCM sustainability framework was developed using an assessment-based approach that integrates subjective and objective approaches to identify the GCM-SI as an assessment method for realizing sustainable development. Therefore, the GCM sustainability indicators are detailed and weighted to identify and analyze contributions through the two global perspectives (SDGs and sustainability pillars) using the analytical hierarchy process AHP.

3.1. Identify GCM Strategies and Types for the Residential Building Sector

To identify the parameters of sustainability indicators, the literature review was thoroughly searched using Google Scholar, Scopus, and Science Direct for publications on sustainable construction materials, green concrete, SCMs, sustainability indicators, residential buildings, CE principles and

strategies, three sustainability pillars, and SDGs. Furthermore, the material durability, strength, maintainability, and workability for GCMs, considering natural resource consumption, energy efficiency, waste management, cost-effectiveness, and keywords, were compiled, as shown in Table 1. This step aims to define and categorize the most important GCM indicators that could contribute to achieving sustainability.

Table 1. Green concrete materials' literature review keywords.

keywords	Synonymous
Green concrete materials	Sustainable concrete - eco-friendly concrete - conscious concrete
Green concrete strategies	Recycled aggregate - supplementary cementitious materials SCMs - innovative concrete technology.
Green concrete types	RAC- FA- CDW- NCA- RCA.
Green concrete component	Sand - coarse aggregate - water – cement.
Environmental impact	CO ₂ emissions - energy use – pollution.
Residential building	Structure building parts – nonstructural building parts.
Green concrete specification	Sustainable methods - alternative materials- code and standards- residential building regulations.
Sustainability assessment	Circular economy principles - SDGs -sustainability pillars.
Concrete performance	Concrete behavior, Properties, strength, durability. maintainability.
Waste reduction	Waste recycling, CDW, by-product.

3.1.1. GCM Specifications and Standards for Residential Buildings

Defining the GCMs sustainability indicators based on the specifications and standards of residential buildings in the Egyptian residential sector. The specifications and standards are benchmarks for quality performance for physical and chemical properties such as strength, durability, etc., and other building functional requirements. This plays a crucial role in quantifying the benefits of using GCMs compared with conventional concrete materials, such as CCMs. Furthermore, ensuring that the GCM production process reaches industrial standards.

3.1.2. Proposing GCM Sustainability Conceptual Indicators Framework

After the previous step, the conceptual framework for GCM's sustainability indicators will be developed based on analyzing these previous and various resources, considering the CE and core principles as a judgment tool for evaluating and adapting. Consequently, selecting the indicators can be suitable for the context of the residential building sector.

3.2. Case Studies

By mapping and screening, the growth of urbanization is expanded based on the new urban development strategy. AutoCAD software will identify and analyze the spatial land use distribution of residential building construction projects and attempt to answer the most common building typology suitable for the study investigation. This led to the identification of the selection area for studies, which consists of two new Egyptian cities, Borg Alarab City and New Cairo City, for applying empirical studies and investigating the effects of using GCM to achieve resource efficiency and sustainability in the new Egyptian cities' residential sector.

3.2.1. Early Design Stage, Case Study I

This step investigates the design role using the design-based solution (DBS) strategy to investigate the use of GCM in the early project stage and its effects on CO₂ emissions, cement, and NA consumption [24].

3.2.1.1. Building Data and Information

This step concerns identifying information and data from the original project documents for the residential building in New Borg Alarab City, Egypt, and it is confirmed by visiting site observation and in-situ measurement.

3.2.1.2. Classify and Quantify the GCM

In this stage, the CCM and GCM in the original and hypothetical building scenarios, such as ordinary Portland cement concrete (OPCC) and RAC made with RCA from CDW concrete debris, are identified and investigated as follows:

The concrete materials are classified into three groups:

- (C1) reinforced concrete with CCM.
- (C2) non-reinforced concrete with CCM.
- (C3) non-reinforced concrete with GCM.

Reviewing the original building design to improve the design based on (re-design and re-selecting techniques for optimum solution), for obtaining the hypothetical design options with the same building dimension and equivalent functionality and durability features. The modified design was suitable for applying GCM for non-structural concrete works and several selected building parts. Combining AutoCAD and Revit to select the most optimum design, AutoCAD is used for initial design concept development and 2D. At the same time, Revit created the 3D modeling, analysis, and documentation. Therefore, both tools promote the investigation of different design options. For example, AutoCAD software reviews and creates 2D drafts for the modified building design details, like floor plans and elevations. This is important for clarifying architectural styles and identifying the layout options of the early design stage.

Furthermore, propose the final building drawings and documents, which include dimensions and specifications. The role of Revit software in residential building redesign is to produce 3D modeling that allows a deep understanding of the building design, component interactions, spatial relationships, and geometry. Furthermore, it enables more investigation of the impact of modifying building components through various design options in the 3D model. Additionally, it facilitates collaboration between the project teams in different disciplines and promotes more sustainability analysis.

3.2.1.3. Identify Concrete Materials

Develop two reference designs (original and modified), which have subcategories (A) and (B) categorized as follows;

- Original A; original design with CCM.
- Original B; original design with GCM.

- Modified A; modified design with CCM.
- Modified B; modified design with GCM.

The proposal to replace the CCM with GCM concrete materials made from RCA is an eco-friendly solution. This was followed by calculating the mix proportions of concrete compositions and the total concrete materials in each scenario to identify the corresponding components, such as cement, sand, natural aggregate, and recycled aggregates, using the absolute volume method (AVM) and Microsoft Excel. Identifying the effect of modified design and the substitution of GCM on the CO₂ emissions from the production of OPC. Early CO₂ estimates based on the CDIAC's method were reported by [52],[147], [148].

Which assumed that cement was of OPC type and the unit quantity per ton, which was reported by [12],[14],[188],[189]. (Griffin,1987 and Andrew R. M 2018) required that cement production data in tons be multiplied by the fixed factor (0.136) to obtain how many tons of carbon are emitted as CO₂. For example, 1-ton cement production caused $0.136 \times 3.667 = 0.50$ tons of CO₂ [3],[4],[18],[19],[23],[43],[46].

3.2.1.4. Compare Concrete Materials for Original and Modified Buildings

A comparative analysis was applied to assess the concrete quantities of the building references after replacing CCM with GCM, using SPSS and Jamovi software to identify the greatest reduction in cement material consumption. This step is applied based on the data collected from the official government documents and original project documents, such as bill of quantity documents (BOQ), original building drawings, feasibility project study, and official contractor documents. Followed materials specifications based on (the Egyptian Standards Specification for Concrete), (the Egyptian Building Code), and supported with the third-party revised report [24].

3.2.2. Construction Process Stage, Case Study II

The second case study concerns selecting the most appropriate and suitable GCMs that can achieve circularity performance during the construction process by developing a simulation model-based Framework (SD-BF) using the SD technique [136], which consists of the following steps.

3.2.2.1 Building Data and Information

Investigate the relationship between different GCM scenarios through the construction process based on the data collected for the family housing building type in New Cairo city using the same previous case study data collection techniques (see section 3.2.2). Furthermore, the project timeline documents are essential for developing the simulation model.

3.2.2.2. Classify and Quantify the GCM

VENSIM and AutoCAD software develop the simulation model based on three concrete types: PCC, RAC, and FA, which are used for classifying five different concrete types as follows;

- Type 1): Portland cement concrete reinforced (PCC-R).
- Type 2): Portland cement concrete non-reinforced (PCC-N).
- Type 3): Fly ash concrete reinforced (FA-R).
- Type 4): Fly ash concrete non-reinforced (FA-N).
- Type 5): Recycled aggregate concrete non-reinforced (RAC-N).

These previous types create seven concrete scenarios (S1...,S7), divided into S1 as an original reference and the remaining six scenarios as hypothetical scenarios.

3.2.2.3. Quantify the Concrete Materials

Quantifying the seven scenarios to investigate the mix proportions of CCM and GCM concrete compositions in their corresponding components for (cement, sand, coarse aggregate, recycled aggregate, (concrete waste, and cost) circularity principles by using the AVM, Microsoft Excel, and MS Project software.

Meanwhile, CO₂ emission was estimated based on the CDIAC's method from cement production reported by [12],[78],[190],[191],[192].

3.2.2.4 Developing the Simulation Model for Optimum Scenarios

Developing a simulation model based on causal loop diagrams (CLD) for causal interdependencies, followed by creating stock and flow (SF) diagrams, presents feedback loops to investigate the inner relations among the

GCMs variables based on the five stages [149],[193]. This will help select the most appropriate GCM scenarios for achieving CE, thereby clarifying and mapping the sustainability assessment for the GCMs in the construction stage. Figure 5 identifies the step-by-step research methodology and structure of case study II research methodology.

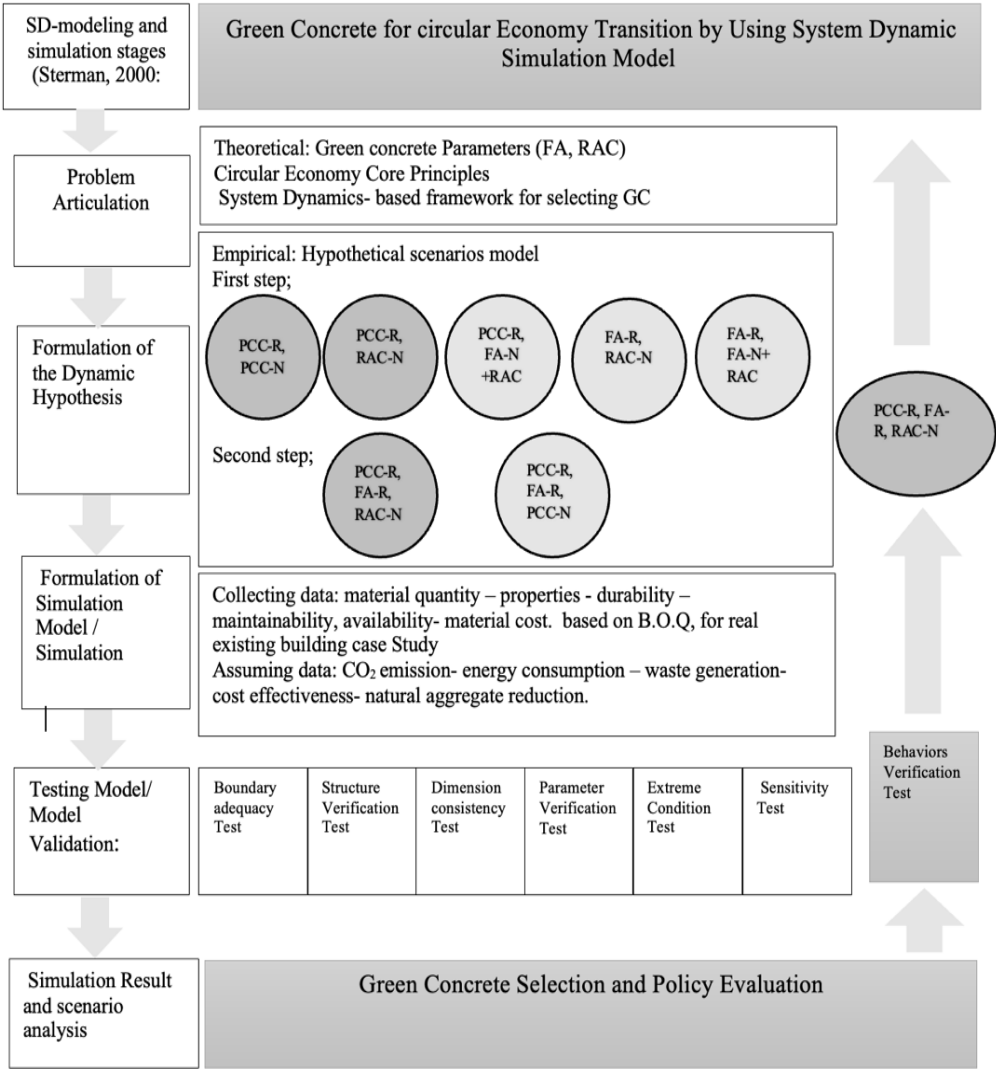


Figure 5. Case study II research methodology structure.

3.3. Developing a Sustainability Framework

The GCM sustainability framework (GCM-SF) was developed to investigate the benefits of using GCM in the construction and design phases for Egyptian residential buildings. The assessing-based approach is used to identify the contribution of the GCMs based on the previous case studies and assessment criteria analysis was linked with the integration of the two sustainability perspectives. The criteria considered CO₂ emissions, energy and resources efficiency, waste reduction, cost-effectiveness, and occupants' comfort level. Achieving that requires a multi-pronged approach to investigate the contributions between GCM, SDGs, and three sustainability pillars consists of the following stages:

First, through literature reviews, the context of sustainability pillars and SDGs is identified and linked with GCMs.

Second, the GCM-SI for the Egyptian residential building sector was obtained based on the data and simulation model obtained from the previous case studies in the design and construction phases. Furthermore, considering the concrete code, green building rating system, government reports, and Egyptian residential building rules and regulations.

Third, investigate the links between GCM-SI, SDGs, and three sustainability pillars by creating the causality relation and contribution by applying weights to various assessment criteria and developing a scoring system for quantifying the performance of each criterion due to their importance for achieving the sustainability goal. Thereby identifies the opportunities and obstacles to using GCM in the Egyptian residential buildings sector. Finally, this is followed by an analysis of the effectiveness of GCM-SF for encouraging scalability contributions; the current stage provides a novel tool and real evidence for environmental scientists, regional developers, construction sector stakeholders, and concrete manufacturers to achieve SDGs in Egyptian residential building projects.

3.3.1. Define the GCM Sustainability Indicators in the Residential Sector

In this stage, the sustainability pillars and SDGs were identified and linked with GCMs. In the current stage, the network analysis technique is used to identify the relationship between the SDGs, pillars, and GCM-SI in the context of the previous Egyptian case studies. Analyzing the link between

GCMs, SDGs, and three pillars by defining the score matrix that connects each target to all the SDGs, whereas each target has been linked with its own goal and other goals obtained from [194]. Therefore, the contribution of GCM-SI and the interconnection within SDGs are defined, and the higher and lower levels are created and modified based on [164],[195]. This followed by an investigation to develop the GCM Sustainability framework for using the GCM in Egyptian residential buildings. Furthermore, identifying the GCM-SI behavior considering the SDGs and three pillars that are interconnected, based on their role, for achieving various SDGs is considered. Meanwhile, seeking SDGs is considered to enhance the achievement of innovative and GCM solutions [26],[69].

3.3.1.1. Selection criteria for GCM-SI list

The indicators were obtained by identifying the parameters and metrics for using GCM and linked to sustainability pillars and the SDGs. Ensure that their specifications and standards are based on the concrete code and green building rating system, and support them with data and information from government reports and Egyptian residential building rules and regulations.

In the same regard, the selection of the indicators has reliability, validity, and applicability for implementation and measures, and they are additionally supported with accessible data to enhance implementation value. Therefore, the indicators of sustainability behavior are suitable for understanding by a wide range of residential sector stakeholders of various backgrounds and realms, which ensures their validity for long-term implementation in the future use of residential buildings.

Notably, the synonymous meaning of indicators is filtered and summarized to become clearer and understandable. Therefore, we integrated GCM indicators in different forms by integrating several indicators into one indicator to reduce complexity. For example, when referring to natural resource consumption, which may be raw materials and/or water consumption, CO₂ emissions are based on cement production, energy use, and transportation [70].

3.3.2. Determine the Contribution

The GCM sustainability indicator contribution determined based on the scoring level is shown in Table 2. The five points (from 1 to 5), one very low and five very high, can be calculated by summing the individual scores. The score is supported by a color scheme to clarify and identify the contribution level between green and yellow. However, the links between GCM, SDGs, and targets may not apply to fall between the five points of the scale system. Still, they reflect the most significant relationships that help achieve sustainability. The highest overall score is considered the most sustainable indicator and can evaluate the GCM in achieving SDGs.

Table 2. The contribution score for GCM for achieving SDGs and sustainability pillars.

Green concrete materials sustainability score	Level
1	Very low
2	Low
3	Medium
4	High
5	Very high

3.3.3. Develop the GCM Sustainability Framework (GCM-SF)

This step proposed the framework to investigate and identify the contributions between GCM-SI, sustainability pillars, and SDGs. After summarizing and combining the indicators, we suggest that 27 indices be identified to clarify and facilitate understanding of the materials’ contributions. The selected indicators are also based on their applicability, reliability, understanding based on the previous case studies and the various stakeholder backgrounds, and the ability for long-term implementation.

3.3.4. Analyzed the sustainability framework

The framework was analyzed and discussed in the context of the potential of the SDGs and three sustainability pillars for future research recommendations. The critical analysis reveals the indicator's behavior that increases sustainability performance and identifies the interrelation for

improving the GCM indicators' positive value. Finally, the final GCM sustainability framework evaluates the scalability of achievement of sustainable development in the future of the Egyptian residential building sector. In this current research stage, the framework was constructed based on the approach described in Figure 6.

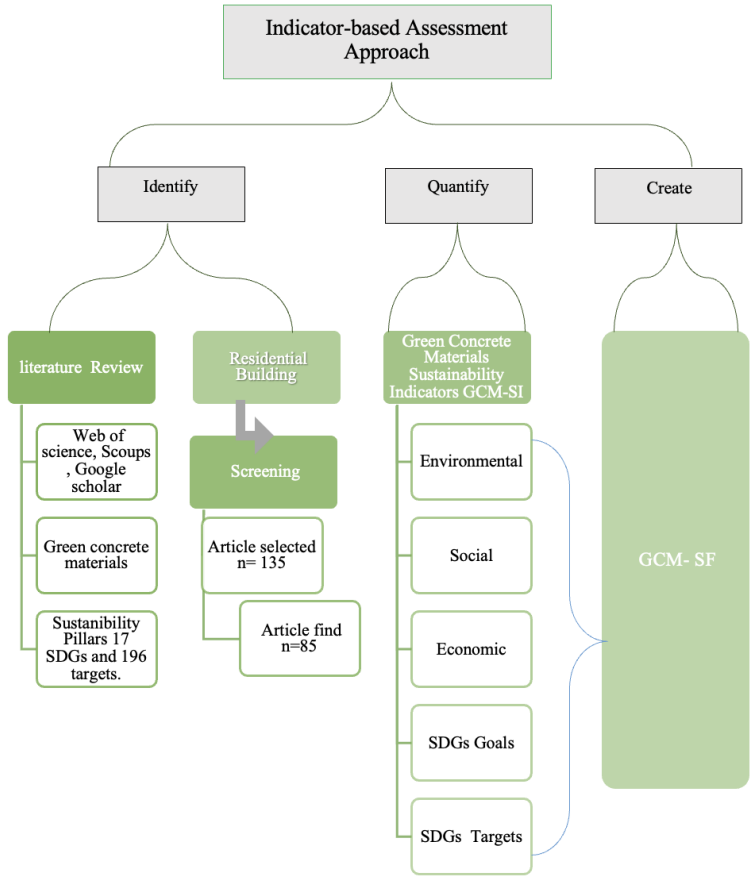


Figure 6. The assessment-based approach for developing the green concrete sustainability framework (GCM-SF).

For more clarity and consistency, the relation between the research goals, research questions, and methodology stage was identified. Table 3 shows the relationship between the research goals, research questions, and the methodology used for the study.

Table 3. Relation between the research's objectives, questions, and methods.

Aims	Questions	Methods
Identify the GCM sustainability indicators (GCM-SI) by proposing a conceptual framework.	How can GCM realize sustainability in future residential buildings?	In stage 1,2 and 3, we investigate the GCM-SI
Investigate the effects of using GCM, in te context of resource efficiency and environmental based on concrete scenarios from the building case study I in the early design stage.	What are the effects of using GCM instead of CCM on cement consumption, natural aggregate, and CO ₂ emissions in the design phase of residential projects?	In stage 1, we identify the benefits of using GCM through Case study I
Quantify and identify the parameters that influence the use of GCM to achieve circular economy (CE).	How can several hypothetical concrete scenarios enhance the selection of GCMs during the construction phase?	In stage 2 Case study II
Create a simulation model to select GCM' circularity performance for future use in residential projects.	How can system dynamic modeling (SDM) improve the selection of GCM to achieve a circular economy (CE)?	In stage 2 Case study II
Develop a GCM sustainability framework (GCM-SF), based on integrating sustainability pillars and SDGs as a governing context.	How can GCM realize sustainability in future residential buildings?	In stage 3, we develop GCM sustainability framework (GCM-SF), based on case study I, case study II, and literature.
Evaluate and enhancing the use of GCM in the residential buildings sector.	How can the green concrete sustainability framework GCM-SF participate in assessing sustainability in the design and construction phases?	In stage 2, and 3, we assess the GCMs' sustainability performance.
Evaluate the contribution of using GCM and its opportunities and challenges to realizing sustainability	What are GCM's contributions to achieving SDGs?	In stage 3, we identify the contributions between GCMs and SDGs

3.4. The methodology limitations

Therefore, the current dissertation discusses the usage of GCMs in the residential building sector in Egypt, which concerns the specific building type, which is the common building type in the study's urban context. Furthermore, the selection of the case studies was limited to the new cities through the government reform strategy, so the choice of the materials is based on that.

However, this methodology also focused on using and selecting GCMs in the early design and construction stages. Therefore, focusing on using different hypothetical concrete scenarios based on the FA and RAC, which are limited for implementation in a low-rise residential building in Egypt. Still, it can be applied to other building typologies in different regions after considering the local building regulations and resource availability.

In contrast, this methodology encounters application difficulties such as limited data, materials specification, local knowledge, and 'awareness for developers and homeowners. Furthermore, there is an absence of regulations that encourage using GCM, labor skills, and SD technique practices in the construction industry and concrete market. Figure 7 illustrates the dissertation and methodology structure. The dissertation structure identifies the chapters, the methods and techniques used, and the collected data to present the research process and workflow step by step. Furthermore, it helps connect the main research points to the methods used to connect with research questions and subsections.

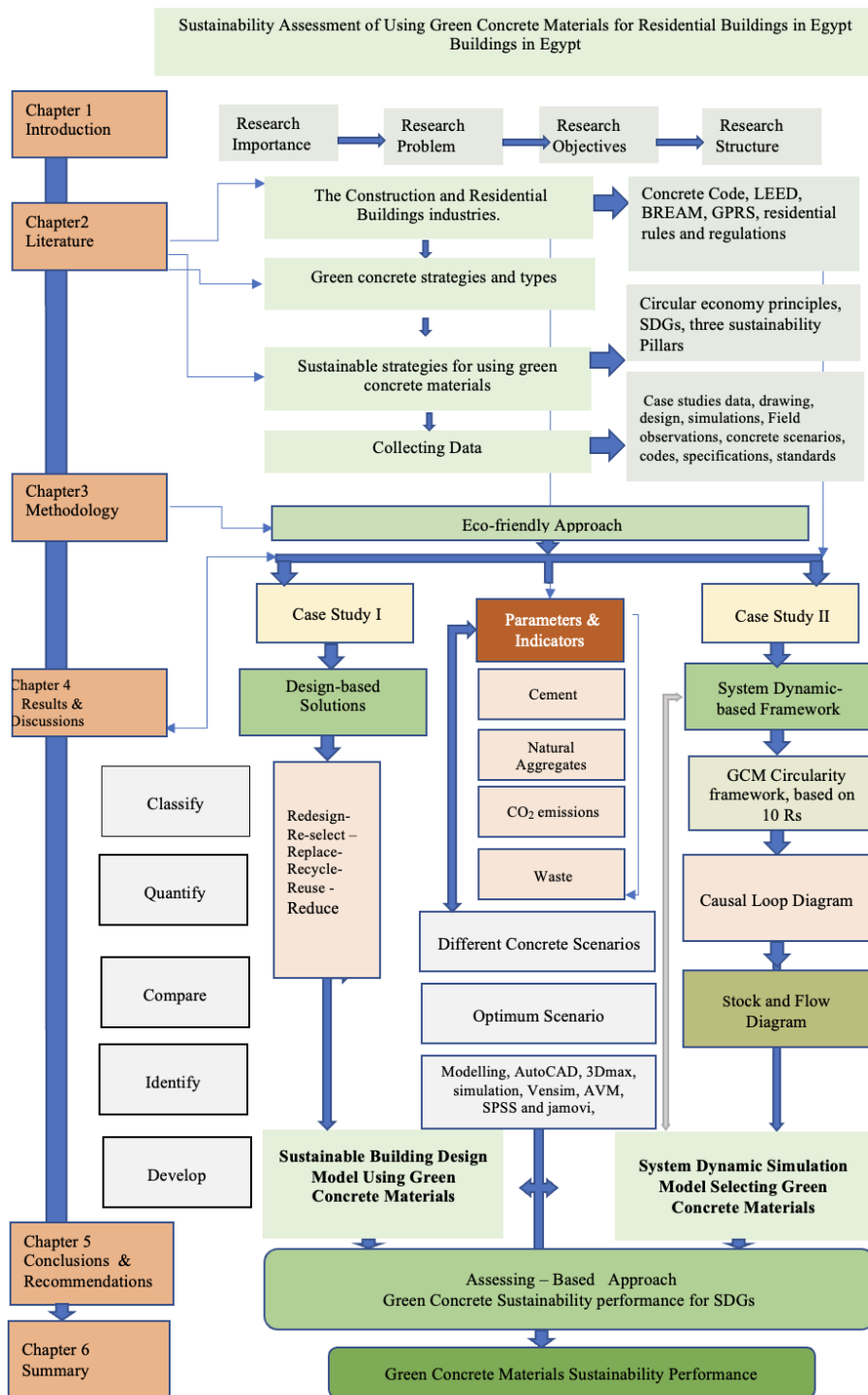


Figure 7 The dissertation and methodology structure.

3.5. Area of Study

3.5.1 New Egyptian Cities

The New Urban Communities Authority (NUCA) was established according to law 59/1979, based on the Egyptian transformation and development strategy for increased urbanization to face rapid population growth. This strategy aims to create new cities to achieve quality of life and economic prosperity. The new area is considered an attraction destination, and the urban extension should be redistributed to the new desert and remote areas, which face urban sprawl in the agricultural lands in the Nile valley. Furthermore, the strategic plan for the selected appropriate sites for constructing the new cities should be applied on different social, environmental, and economic bases.

The general structure of new Egyptian cities includes the common elements of sustainable cities. For example, the core elements consist of residential districts, including various housing types and most amenities, and various services to address different categories of population needs, supported by commercial and business districts. These cities are designed to meet sustainability principles, emphasizing eco-friendly practices, energy efficiency, and resource conservation. Additionally, they support innovative technologies in infrastructure management and citizen services.

New urban communities promote the planning of new cities by using the latest innovative and sustainable urban systems. For instance, NUCA emphasizes increasing the availability of low-income and economic housing units, which raises the quality of life in society. Consequently, NUCA has promoted several housing projects that can be suited to different inhabitant levels and have all amenities and facilities. In this regard, Egypt has undergone an urban transformation in the last three decades by establishing and constructing several new cities according to law (59/1979) all over the country. These projects aim to reduce the overcrowded pressure on the old and existing cities, improve the quality of life, promote modern living standards, and create socio-economic hubs. These new cities aim to achieve Egypt's vision for a sustainable future (New Urban Communities Authority).

3.5.1.1.New Borg El Arab City

New Borg El Arab City is considered the first city of four generations of new Egyptian cities. It is an important growing urban center located about 55 km from Alexandria, about 8 km from Egypt's Mediterranean coast, and about 3 km from Borg El Arab City. It has a dry and humid climate, is 28 meters higher than the sea level, and has a total area of about 191 Km². It was established to extend Alexandria city and absorb the rapid population growth. [196]. Therefore, the selection of this city for investigating using GCM due to the urban context, including a large number of new residential projects that are considered common building types, which have a great chance and ability to utilize eco-friendly materials furthermore a crucial impact on achieving sustainable practices. There are about thirteen residential neighborhoods, including various residential building types with all the amenities such as schools, government services, commercial centers, hospitals, and sports clubs, adding to ten industrial zones with various industrial activities.

According to the statistics for 2022, the population reached about 170,000 people [197]. The city is designed based on sustainable urban development by incorporating advanced and green infrastructure. It promotes a planned community with a great opportunity to apply GCM, natural resource management, and environmental protection strategies that enhance urban planning principles and realize sustainable development [196],[198]. Figure 8. illustrates the New Borg El Arab City map.



Figure. 8 Location map of the study area, building case study I, and building location in New Borg El-Arab City in Alexandria, Egypt, source (Google Maps, 2024).

3.5.1.2. New Cairo City

New Cairo was established in 2000, and three towns were merged into settlements. It started on an area of about 67,000 acres, then extended to become 85,000 by 2016. The city could eventually host a population of 5 million in 2017. According to the “New Urban Communities Authority” (NUCA), the city’s population was estimated at 1.5 million, with an expected growth target population of 4 million. In this regard, Figure 9. identifies the location of new urban communities in New Cairo City. The city is located in the Egyptian eastern desert, built east of Cairo city, which ranges 820 and 1,007 ft) above sea level. Figure 10. illustrates the Cairo context map with new urban areas. Furthermore, the location of the building case study II is defined as shown in Figure 11 (New Cairo City, Egypt (Google Maps, 2024).

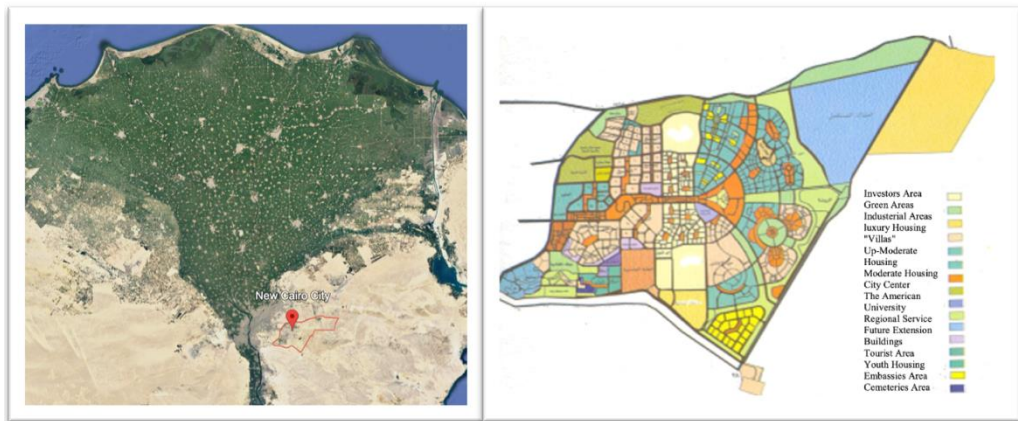


Figure 9. Left-side Building location in New Cairo City, Egypt, and right-side general plan of New Cairo City, source (Google Maps, 2024)[199,200].

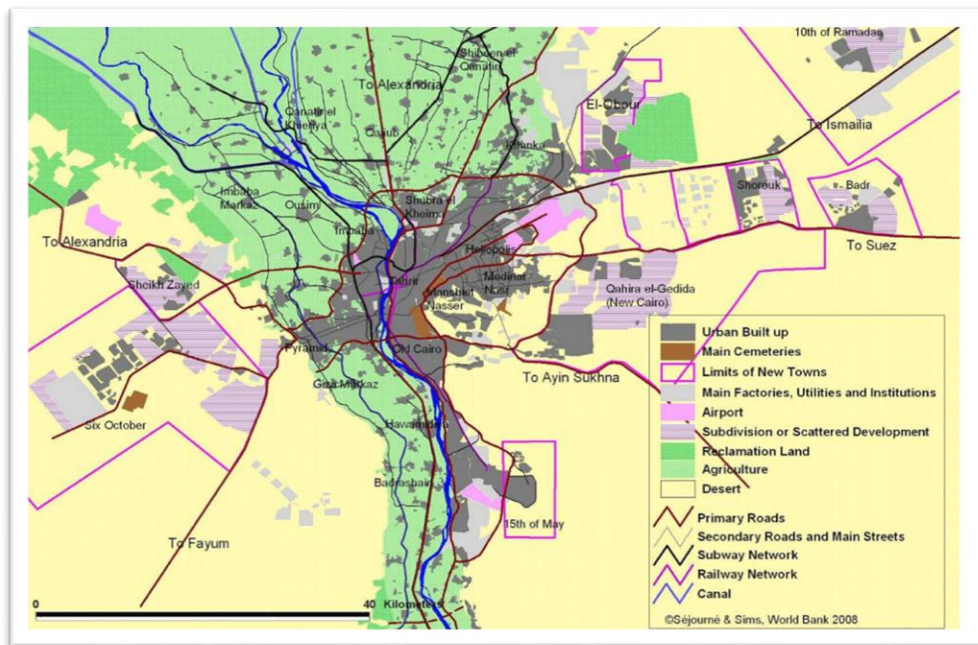


Figure 10. Cairo context map, with new urban areas [200].

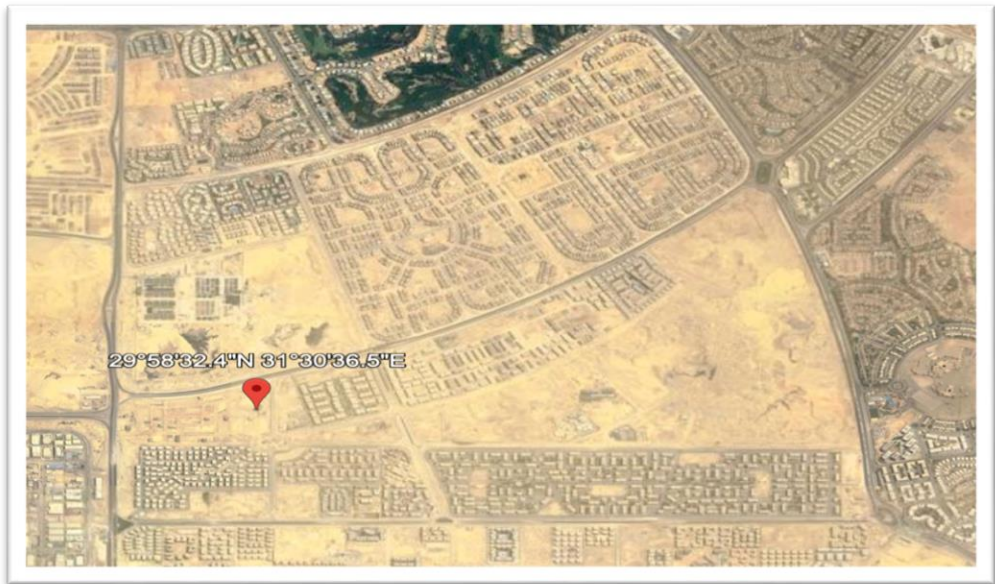


Figure 11 Location map of the study area, of building case study II (New Cairo City, Egypt (Google Maps, 2024).

4 RESULTS AND DISCUSSION

4.1. Investigation of Egyptian Residential Buildings

In Egypt, the most residential building typologies in the Egyptian new cities are (multi-family apartment buildings, Townhouses, Villas, and Single-family houses). The total number of residential units by 2021/2022 reached 246.1 per thousand units, with an investment of about (143.5 billion) Egyptian pounds (LE), compared with 2020/2021, which scored 336.3 thousand units with 150 billion pounds investment. Figure 12 shows the distribution of building types according to their construction type.

In contrast, Economic housing reached 139.8 thousand units by 57%, followed by average housing with 69.8 thousand units, and achieved 28% Followed by luxurious housing, and above-average housing reached 22.6 and 13.8 thousand units and accounted for about 9%, and 6% respectively of the total residential unit in 2021/2022 (Annual Bulletin of Construction and Buildings).

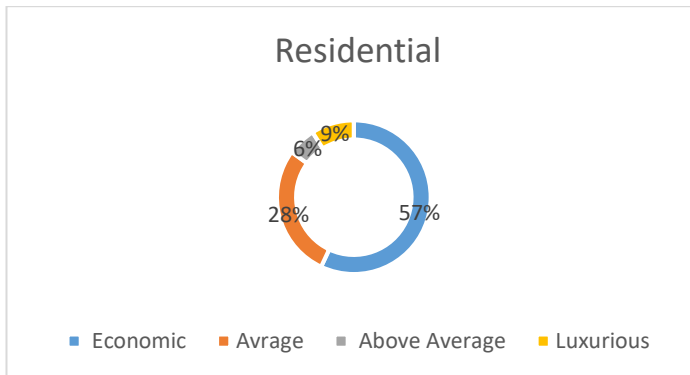


Figure 12. The number of residential building units and types in Egypt 2021/2022.

4.1.1. Description of Egyptian Residential Building Types

The variety between public and private residential building types was found to promote the rights of a wide range of populations to improve their quality of life at all societal levels. Furthermore, the cooperation between the

public and private sectors has resulted in different sizes and prices for residential units. For example, the year 2021/ 2022 is shown in Table 3. Economic housing was described for youth and low-income people; its area reached 90 m², usually three rooms. Similarly, the average housing area is between 100 and 150 m² and consists of 3 rooms, which is recommended for middle-income citizens. Otherwise, prompted for high-income citizens, a type of luxury housing usually described as villa-type with a private garden and/or located inside a closed compound with a guarded system, considered gated communities.

Table. 3 The residential types of public and private sectors by 2021/ 2022.

Unit Types	Public/ thousand units	%,	Private/ thousand units	%	Total	Investment/ billion pounds
Economic housing	97.30	74.5%	42.5	36.8%,		
Above average housing	16.30	12.5%	53.5	46.3%,		
Average housing	00.14	0.1%	13.7	11.9%,		
luxurious housing	16.80	12.9%,	5.8	5%		
Total	130.50	100	115.5	100	246.1	143.5

Meanwhile, the Cairo governorate ranked first, followed by Alexandria, in the number of building units in the public and private sectors, with 50.1 and 26.5 thousand units and 38.3% and 23%, respectively. Therefore, the two new cities were selected as study areas due to their tremendous importance in facing the population growth and high density in the two capital cities, Cairo and Alexandria, in Egypt. Furthermore, they have an essential role as a representative of the situation in Egypt and allow us to draw insight into investigation for applying the development strategy.

4.2. Case study I

4.2.1. The Building Data and Information

This case study was applied to the residential building project during the early design phase. The building location is shown in Figure 13, located in the urban scope of (New Borg El-Arab City), Alexandria Governorate, Egypt. The building is considered a standard family building and the most common building typology within the Egyptian government's development program. Therefore, this type has the flexibility to apply GCM, encourage sustainable construction materials, and realize sustainability. Additionally, Figure 14 illustrates the general strategy plan for New Borg Alarab City and describes the land use for residential buildings and other building types in the urban context.

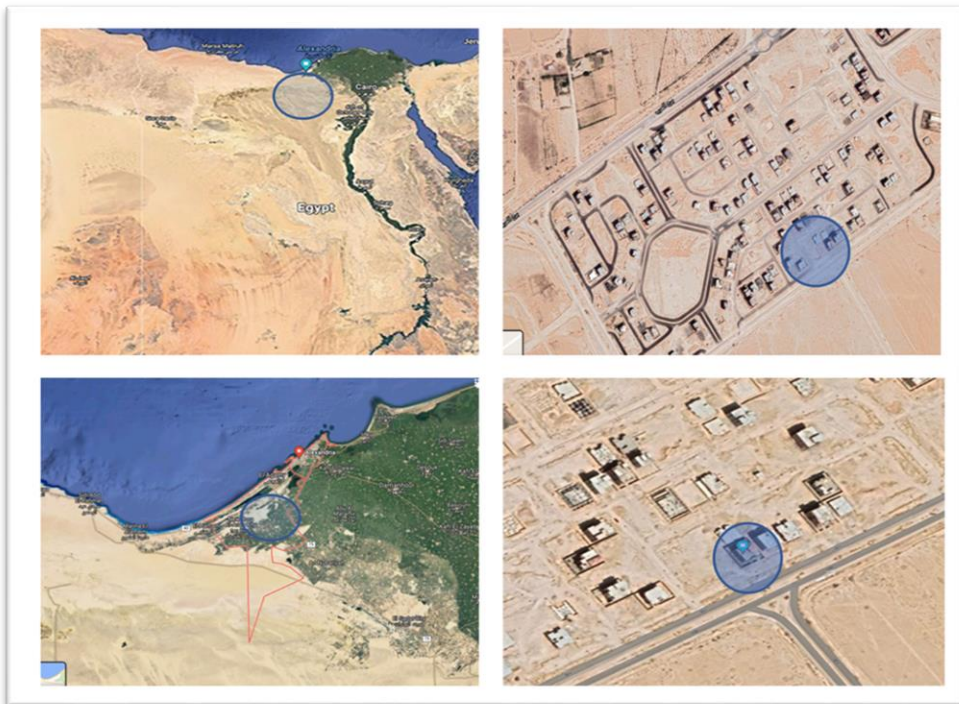


Figure 13. The building is located in New Borg El-Arab City in Alexandria, Egypt, source (Google Maps, 2022).

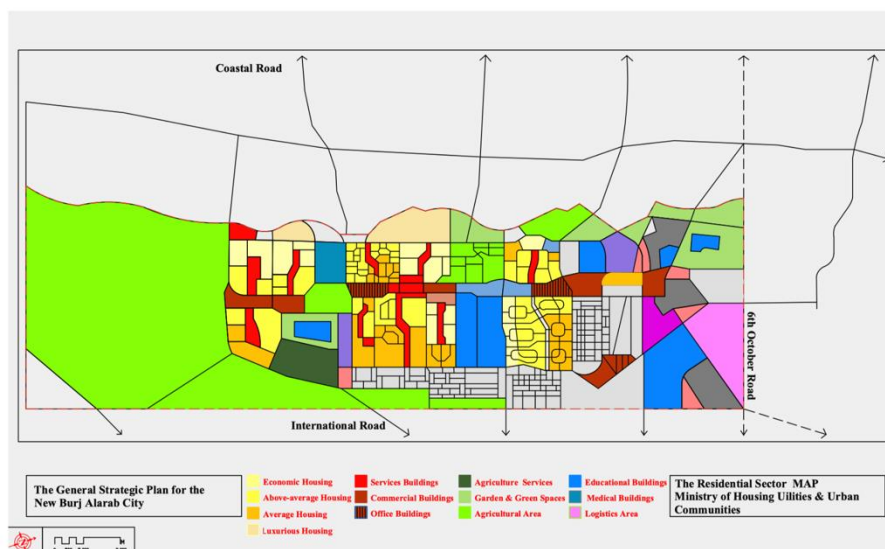


Figure 14. The general strategy plan for New Borg Alarab City, (source author Modified based on) [196].

In this case, the modified design presented a hypothetical option for the GCM standard since the building data and information were collected from BOQ, official project requirements and reports, the original project plan, in situ measurements, and official government documents, such as Egyptian building code and building authority regulations [192],[193]. Thus, the data are considered valid, precise, reliable, and suitable for use in all the project phases and each selected building part. Furthermore, it was revised and signed by a third-party consultant team to ensure that it meets the Egyptian building code specifications and is valid with the residential construction regulations.

4.2.2. Original and Modified Building

The result showed that the modified building design considers all the essential building elements of the original design and their corresponding parts. Furthermore, it has the same building dimensions and equivalent land use. Table 4 shows the basic data and information, such as floor space area, dimensions, and building parts.

Table 4. The original building data and information.

Building Part	Dimensions			Floor Space Area, m ²
	Length, m	Width, m	Height, m	Area, m ²
Basement	14.39	13.40	13.50	192.81
Ground floor	15.54	13.65	4.00	212.09
First floor	15.54	13.65	3.50	212.09
Penthouse	6.13	8.00	3.00	49.01
Total build area				666.00
Total land area	20.00	25.00		500.00

4.2.2.1. The Role of Design for Applying GCM

In this stage, the original building design was modified, concerned with the selected specific building parts suitable for applying GCM. Meanwhile, based on the parameters, the materials selected included concrete quality with recyclable materials, considering equivalent CCM's durability, strength, and functionality. In this regard, RAC, produced from local CDW, was selected due to its ability to reduce natural aggregate consumption and waste generation. Therefore, GCM is applied for non-structural works as (C3) in the selected building parts, with the same strength and durability to play the same function role. In all scenarios, even in original and modified buildings, reinforced concrete was applied in the building parts, such as beams, columns, suspended slabs, and staircases. Notably, non-reinforced concrete was applied to internal building parts such as secretes, lintels, lift walls, wall boundary panels, printed concrete, and entrance steps, while carp stone, soft landscape, flowerbeds, and pavement were applied to external parts. The final selection of non-structural building parts is shown in Figure 15.

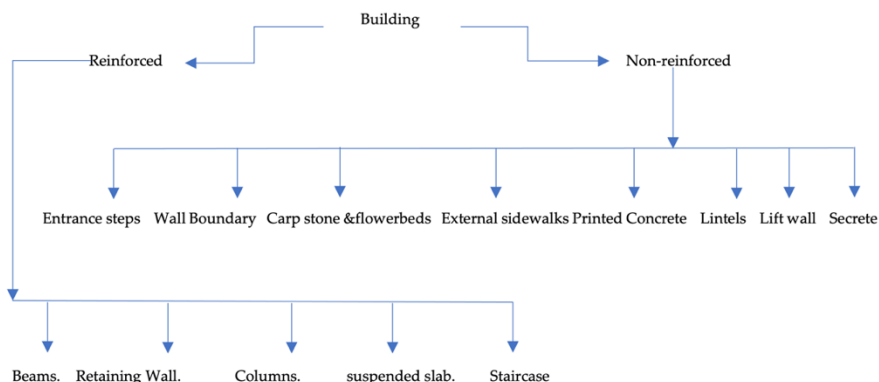


Figure 15. The selected (structural, & non-structural) building parts.

4.2.2.2. Modifying and Original Building Design

By optimizing the building's original design, we found that the modified design reduced the CCM consumption that accrued in the internal space area, such as the basement and on the ground floor. These areas were optimized by reducing the number of unnecessary walls and staircases. Furthermore, the aesthetics of the building were improved by enhancing the external decorative works, landscape, sidewalks, and entrance. Figure 16 shows the original and modified designs' front elevation, typical site plan, and the basement, ground floor, first floor, and penthouse floor.



Figure 16. (a) Original design front elevation (left) and the typical site plan (right). (b) Modified design front elevation (left) and the typical site plan (right), (source, author).

In this stage, the modified design promotes the first attempts at a sustainable building model using GCM in residential buildings, thereby being considered as a starting point and indicator for meeting sustainable construction practices that help for sustainable strategies such as material efficiency and cost-effectiveness during the construction phase.

4.2.3. Classifying The Concrete Materials

In this section, the concrete materials are classified into three categories: first, C1, which is (reinforced concrete), PCC, used for [panels, beams, suspended slabs, foundations, and staircases). Second, (C2) is a (non-reinforced concrete) with OPC used for different fundamental construction works, such as entrance steps, wall boundary panels, carp stones, flowerbeds, soft landscapes, walkways, printed concrete, lintels, lift walls, and secretes. Third, C3 which is a (non-reinforced concrete), RAC made from RCA obtained from CDW. These are considered the most important and common construction materials worldwide and are usually used for general uses in Egypt. Therefore, the selection of concrete materials, depending on their functionality and durability, thereby applying different concrete mixes, such as 1:4:8 (M10) and 1:2:4 (M15) for non-structural selected building parts and 1:1:2 (M25) for structural parts such as beams, columns, and foundation. However, considering the same design, GCM quantities are estimated for non-structural works in the selected parts. Therefore, the cement, natural aggregate, and sand for each reference and hypothetical design volume are calculated by AVM, Microsoft Excel, and a rectangular cross-section of each building part based on BOQ.

4.2.3.1 Concrete Materials' Quantities for Specific Building Parts

This is the first attempt to reduce the total consumption of concrete materials through design modification before integrating GCM. It recorded a reduction in CCM quantities by 8.14% from (original A) to (modified A). Table 5 shows the C1 and C2 quantities for original A and modified A in the selected building parts. Additionally, the result identified the relationship between the selected building parts and (C1 and C2) quantities.

Table 5. The concrete quantity (C1& C2) in selected building parts for original and modified building designs.

Concrete Specification	Building Part	Concrete with Ordinary Portland Cement	
		Original Building A C1 and C2, m ³	Modified Building A C1 and C2, m ³
Non- structural concrete	Internal floor (secrete)	47.8	52.9
	Wall boundary panel	26.5	26.5
	External sidewalk, carp stone, printed concrete	38.9	38.9
	Internal walls (lintels and lift walls)	37.5	36.8
	Entrance steps	3.6	3.6
		347.3	302.0
Structural concrete			
	Total concrete	501.5	460.7
	Percentage	100%	91.9%

Due to the design modification, the internal floor area increased; consequently, the CCMs quantity in modified A increased compared with the original, as shown in Figure 17.

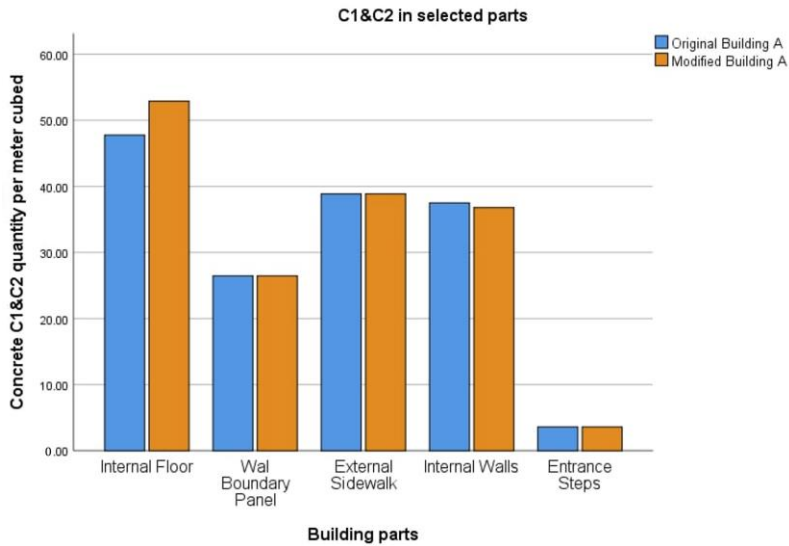


Figure 17. The relationship between selected building parts and C1 and C2 concrete materials in original A and modified A.

4.2.3.2 Concrete Materials for Selected Building Parts

The result showed a reduction in the concrete quantity from [original A, (C1 & C2)] at (347m³) and (154m³), respectively, to [modified B, (C1& C3)] at (302m³) and (159m³), respectively. On the other hand, the cement quantity in [original A, (C1 and C2)] was (189kg) and (48kg), respectively, while in [Modified B, (C1, and C3)], it was (164kg) and (27kg), respectively. Table 6 quantifies the materials consumption by using (C1, C2, and C3) as concrete material through all building scenarios: original A, original B, modified A, and modified B, respectively. Furthermore, the quantity for each reference for natural coarse aggregate (NAC) and sand.

4.2.4. The Selection of the Most Optimum Building Scenario

Based on the previous section, (Modified B), which contains the GCM as a (C3), is considered the optimal building scenario with cement consumption of about 191kg, representing 80.6% of the total concrete materials. Additionally, there are no significant differences between (Original B), the cement consumption of which is (215kg), and (Modified A), for which this value is (214kg). However (Original A) is the most cement consumer, with a total of (237,002 kg). On the other hand, the quantities of sand, natural coarse aggregate, and RCA show a significant reduction. Therefore, modified B was considered a significant building reference in reducing materials and was selected as the optimal reference for cement, sand, NA, and RCA, as shown in Table 7.

Table 6. The cement and concrete quantities for all building scenarios.

Original Building A and B and Modified Building A and B								
	Original A		Original B		Modified A		Modified B	
Total Concrete, m ³	502		502		461		461	
	C1	C2	C1	C3	C1	C2	C1	C3
Concrete, m ³	347	154	347	154	302	159	302	15
	Cement, Sand, Natural Aggregate, and RCA							
	CI	C2	CI	C3	CI	C2	CI	C3
Code Specification	1:1:2	1:2:4	1:1:2	1:4:8	1:1:2	1:2:4	1:1:2	1:4:8
Cement/ton	189	48	189	26	164	49	164	27
	237		215		214		191	

Table 6 (continue). The cement and concrete quantities per ton are for all building scenarios.

Original Building A and B and Modified Building A and B							
Cement, %	100%		90.1%		90.2%		80.6%
Sand/ton	410	208	410	112	357	214	357 115
	618		522		571		472
Sand, %	100%		84.5%		92.3%		76.3%
NA/ton	715	362	715	--	622	373	622 ---
	1077		714		994		622
RAC/ton	100%		66.3%		92.3%		57.7%
	---	---	---	195	---	---	---- 201
	---		195		---		201
	1077		910		994		822
Aggregate, %	100%		84.5%		92.3%		76.3 %

Table 7. The quantities of C1 and C3 concrete in modified building B.

C1	Concrete Component C1, Modified Building B.		
	Cement	Sand	Aggregate
Mix/Ratio	1	1	2/NCA
ton	164	357	622
C3	Concrete Component C3, Modified Building B		
Mix/Ratio	1	4	8/RCA
ton	27	115	201

4.2.4.1 The Steps for Reducing Cement Material

The reduction for the cement materials consists of three steps: The first reduction recorded was 9.3% due to (Original A) being modified to (Original B). The second reduction recorded was 10.7% due to applying GCM via (Modified A) and (Modified B). The final reduction between (Modified B) and (Original A) was 19.4%, a positive indicator of reducing negative environmental impact and realizing sustainability. Table 8 illustrates the reduction steps in detail.

Table 8. The reduction in concrete and cement quantities through the three steps of the modified process.

First							Notes
Description	Original Building						
	Original A			Original B			
Concrete type	C1	and	C2	C1	and	C3	
Concrete type/m ³	347.3		154.1	347.3		154.1	Total saving of cement (OPC) in the project. 9.3%
Total concrete, m ³		501.5			501.5		
Cement, ton	189.0		47.9	189.0		25.8	
Total cement, ton		237.0			214.9		
Cements, %		100%			90.7%		
Second							Notes
Description	Modified Building						
	Modified A			Modified B			
Concrete type	C1	and	C2	C1	and	C3	
Concrete type, m ³	302.0		158.6	302.0		58.6	Total saving of Cement (OPC) in the project. 10.6%
Total concrete, m ³		460.7			460.7		
Cement, ton	164.4		49.3	164.4		26.6	
Total cement, ton		213.7			190, 9		
Cements, %		100%			89.4%		
Third							Notes
Description	Original Building A and Modified Building B						
	Original A			Modified B			
Concrete type	C1	and	C2	C1	and	C3	
Concrete type, m ³	347.3		154.1	302.0		158.6	Total saving of cement (OPC) in the project. 19.4%
Total concrete, m ³		501.5			460.7		
Cement, ton	189.0		47.9	164.4		26.6	
Total cement, ton		237.0			190.9		
Cement%		100%			80.6%		

4.2.4.2 Comparison Analysis of CCM and GCM

A comparative analysis was applied to the quantities of CCM and GCM in all Scenarios and their components, presenting the relationship between the CCMs' quantities and their components before adding GCM. The results showed that reducing raw materials consumption after using RAC and (Modified B) (Modified B) provides the optimal reduction in cement, sand, and NA consumption, as shown in Figure 18.

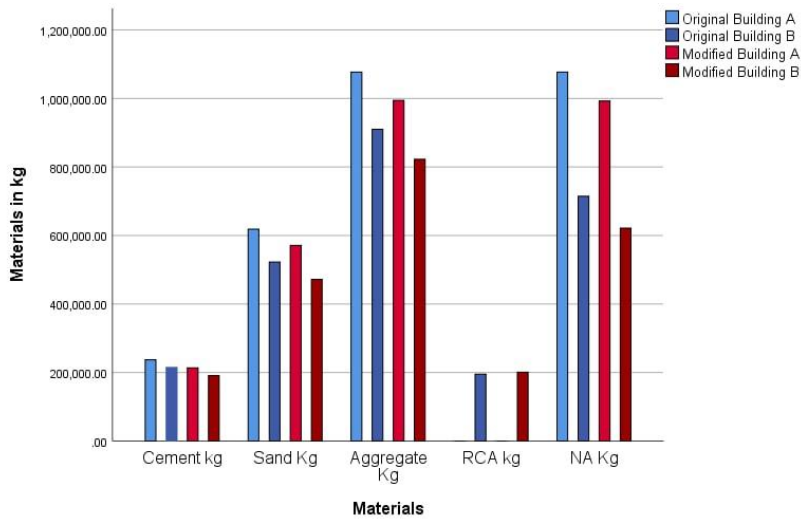


Figure 18. The distribution between the CCMs and CCM quantity components, cement, sand RCA, and NA.

4.2.4.3 Cement Production and CO₂ Emissions

In this section, the CO₂ emissions were estimated for cement production, assuming that OPC is the cement used. Consequently, the quantity of cement is calculated per ton using (CDIAC's method) [188,189]. Consequently, emissions estimates showed that (Original A) cement consumption is [236.9 tons] and produced [118.45 tCO₂], (Original B) cement consumption is [214.8 tons], and produced [107.4 tCO₂], (Modified A) cement consumption is [213.7 tons], and produced [106.85 tCO₂]. Finally, (Modified B) cement consumption is [191.0 tons], and it is produced [95.5 tCO₂]. Therefore, the reduction in CO₂ emissions from (Original A) to (Modified B) was 22.95 tCO₂, representing a 19.4% reduction. Table 9 shows the relationship between the Original and Modified building scenarios regarding structural and non-structural concrete. Whereas the current research has been limited to investigating cement consumption in specific and selected building parts, the results show that (Modified B) contributed a 19.5% reduction in cement consumption from (Original Building A). Therefore, the cement consumption was reduced by 44% for the non-structural building parts, considered a positive indicator in environmental conservation and promoting sustainable development, and should be considered for future residential projects.

Table 9. The cement consumption/ton and cement reduction for all the building scenarios.

Original Building A and B and Modified Building A and B								
	Original A		Original B		Modified A		Modified B	
Concrete, m ³	501.51		501.501		460.68		460.68	
Mix type	CI	C2	CI	C3	CI	C2	CI	C3
Cement, ton	189.0	47.9	189.0	25.9	164.4	49.3	164.4	26.6
Cement, ton	236.9		214.8		213.7		191.0	
Cement C1, C2 and C3 %	100%		90.07%		90.2%		80.6%	
Cement C1, C2 and C3 Reduction %	100%		-9.3%		-9.8%		-19.5%	
Cement C2 and C3, ton	47.9		25.9		49.3		26.6	
Cement C2 and C3 %	100%		53.8%		102%		55.5%	
Cement C2 and C3 reduction %	100%		-46.2		+2.9%		-44.5%	

4.2.4.4. The Most Benefits of Using GCM

According to all previous studies, cement consumption and reduction have a strong relationship with the order process for the previous building scenarios; for example, we noticed that (Modified A) had the highest cement consumption due to increasing the floor area. Meanwhile, (Modified B) is considered the most optimum scenario for reducing cement consumption and CO₂ emissions by 44.5% compared with (Original A). This result indicated that it should be concerned with applying this strategy in the same order to obtain the most benefits and optimal results to achieve optimum cement consumption. Figure 19 illustrates and clarifies the cement amount among concrete types C1, C2, and C3 regarding structural and non-structural works for all scenarios (Original A, Original B, Modified A, and Modified B) based on the production of OPC. Furthermore, the cement amount in C2 and C3 considers non-structural works for each building scenario.

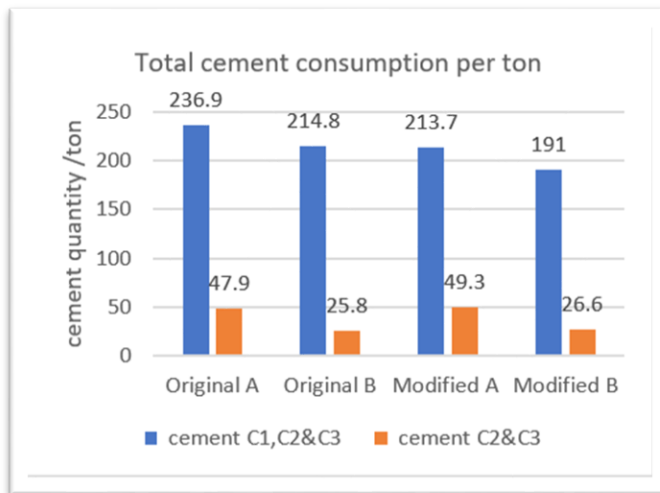
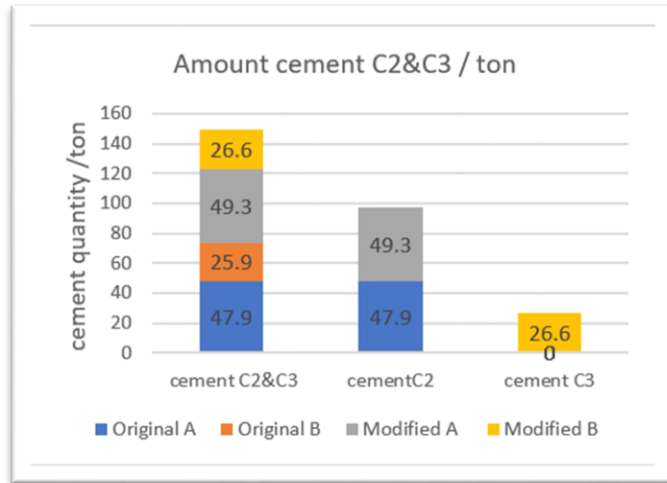


Figure 19. The relation between cement consumption and all scenarios.

Therefore, in this case study, the investigation was concerned and limited to the non-structural works in selected building parts. Using RCA produced locally from CDW allows for more opportunities and investigation in some cases and plays a vital role in protecting the environment and enhancing sustainability practices in the construction sector at the local and international levels.

4.2.4.5. Sustainable Building Model I

For more clarification of the benefits of using GCM, Finally, the most optimum scenario has the benefits of using GCM, which is considered (Modified B); thereby, the 3D model was created to be considered as a clear guide to reflect the conceptual framework for using GCM in the early project stage.

In this stage, the framework summarizes the design process, starting with redesigning and modifying the original building design to develop a conceptual reference that can substitute CCMs with GCMs in specific selected building parts. This is followed by reusing recycled materials such as RCA, made from CDW, to reduce natural aggregate, cement, and CO₂ emissions. This result considered the final optimal model as a guideline for environmental protection and construction industry stakeholders. This can help decide new rules and regulations regarding GCM used in residential buildings. Additionally, it presents evidence for the crucial role of the design phase in concrete and cement consumption for the sector, which positively impacts on applying sustainable construction materials on a wider scale nationwide. Figure 20 shows the concept design framework and its contribution to material consumption and environmental protection.

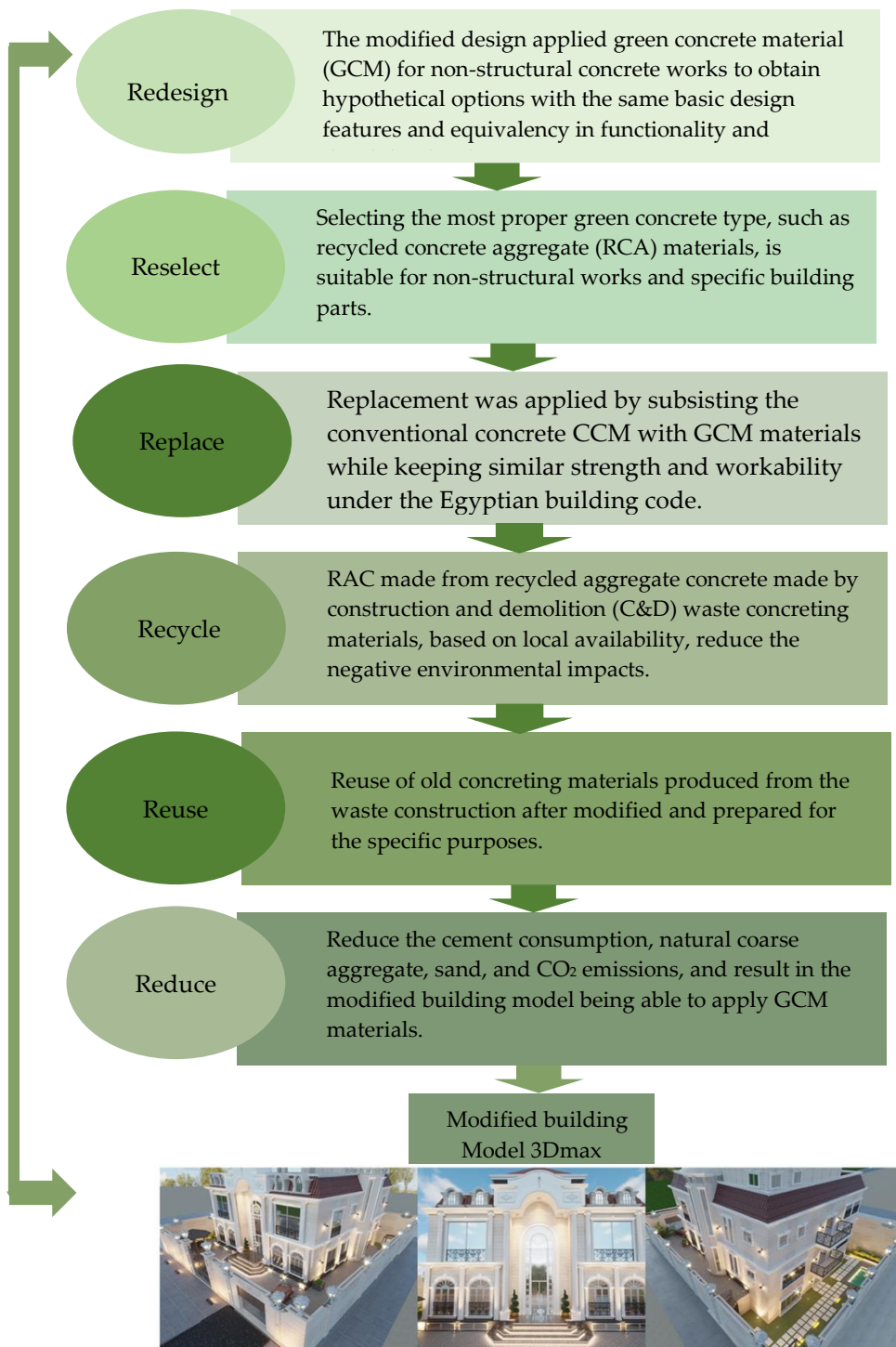


Figure 20. The conceptual design framework of applying GCM to the building scenario, Modified B, with the 3D model (source author).

4.3 Case study II

4.3.1. Building Location and Map

The second case study is a project of a new residential building in New Cairo City, Egypt. The study aims to investigate the selection and effect of using GCM to apply circularity performance during the construction phase by using SD. Since the building case study II is considered the most common building typology in the new urban context of New Cairo City, as shown in Figure 21, Economic and Social housing are given tremendous attention and priority in the development strategic plan [24],[130].

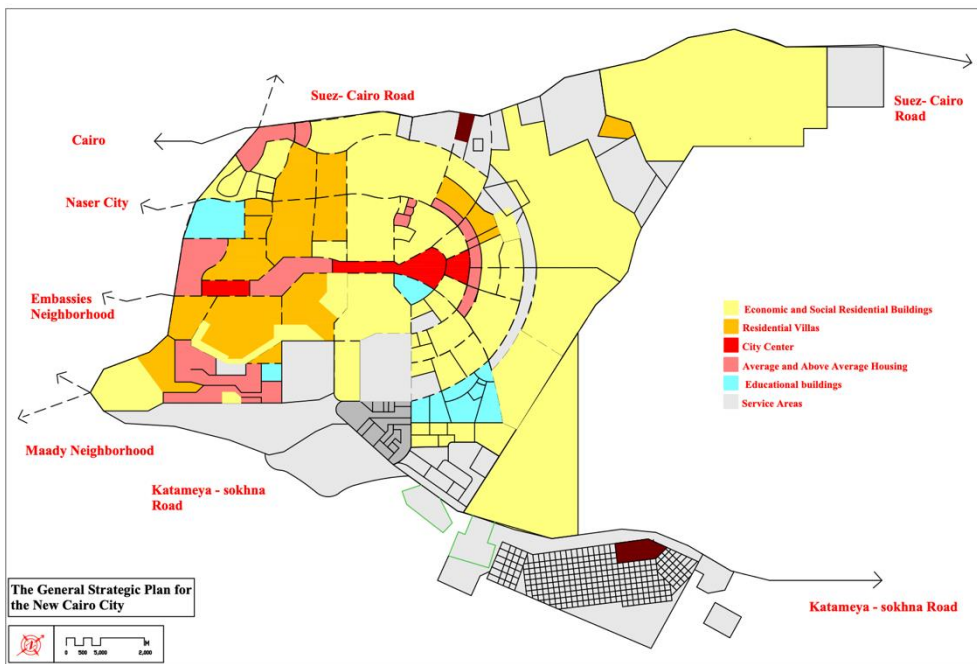


Figure 21. New Cairo City general strategic plan (source author, based on) [199].

4.3.2 Building Data and Information Case Study II

The building's structural system is reinforced concrete (RC), based on the data collected from the building's official documents, consultant, project timeline, and official government documents, supported by site observation, land area measurements, and discussions with the project team and consultant experts.

In this regard, AutoCAD details the geometric information and measurements for various building components like walls, floors, and roofs. This provides important data for calculating the required building concrete material for the construction process during the 30 months. Therefore, Table 10 identified the building dimensions, area, and information.

Table 10 The Building 2 Dimension and Information

Description	Area dimension (m)	Floor area (m ²)	Building height (m)
Total land area	29.2 x 21.9	639.9	-
Basement	16.9 x 14.8	249.9	3.4
Ground floor	17.5 x 15.7	274.1	4.0
First floor	17.5 x 15.67	274.1	3.6
Penthouse	8.8 x 14.8	130.1	3.1
Total built area	-	928.2	-
Total building height	-	-	12.0

4.3.3. Case Study II Building Drawing

The building drawing was created based on consistent standards, ensuring accurate building information. The AutoCAD drawings are considered the foundation used to update the project progress and identify the required adjustments by calculating volumes and concrete material quantities in all the construction process steps. This ensures accurate and reliable estimation of the quantity of the material needed. According to the site visits and observations, urban sprawl is increasing due to the same building type in the urban context. Figure 22 describes the building case study II land area before construction. Additionally, Figure 23 illustrates the building drawing, identifying the front and rear elevations and the ground floor plan.



Figure 22 The location of building case study II before the construction process (source author).

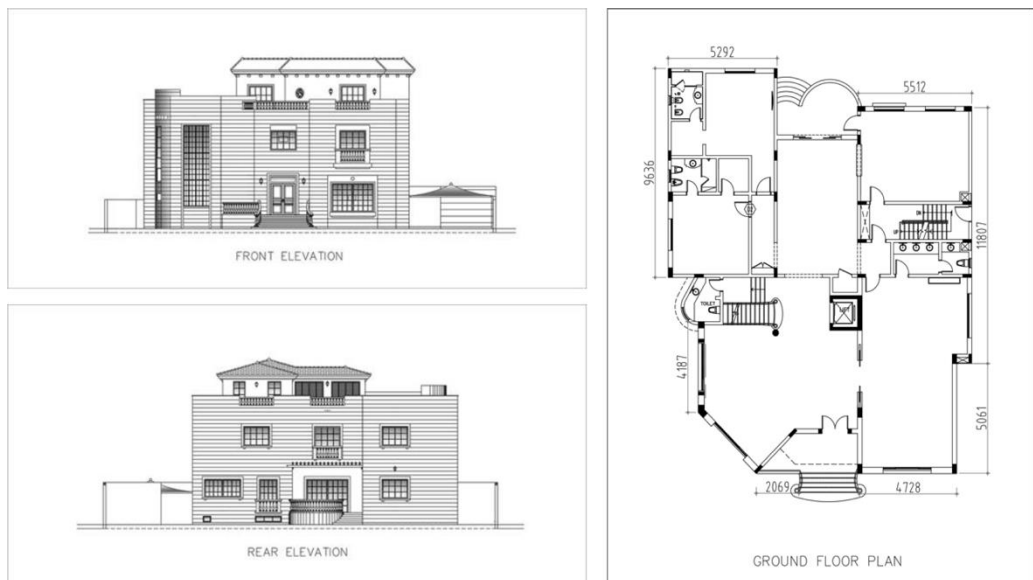


Figure 23. Building drawing and site plan (source author).

4.3.4. GCM Classification for Case Study II

In the current stage, more CGM is used and investigated, such as FA, RAC, and PCC, furthermore utilized in several concrete hypothetical scenarios to add valuable insight through the simulation process, allowing more circularity and resource efficiency based on the CE core principles. Therefore, the variety of concrete types, such as C1 (PCC-R), C2 (PCC-N), C3 (RAC-N), C4 (FA-R), and C5 (FA-N), as shown in Fig 5. Whereas the classification of the hypothetical different GCM scenarios is based on the CCM scenario, considering the application of the construction process and their suitability and local availability. After defining the concrete types, the original scenario S1 will be categorized, followed by other scenarios (S2, S3, S4, S5, S6, and S7). Then, we identified the concrete function [FA-R & PCC-R] used for reinforced concrete and [PCC-N, RAC, and FA + RAC] for non-reinforced. Therefore, each scenario quantity is calculated considering the building dimensions and areas for the concrete quantity by using AVM, standard formulas, and conversion factors. The total concrete quantity showed a constant value of 482.16 m³ in all scenarios. In this stage, the concrete materials for the building are classified as shown in Figure 24.

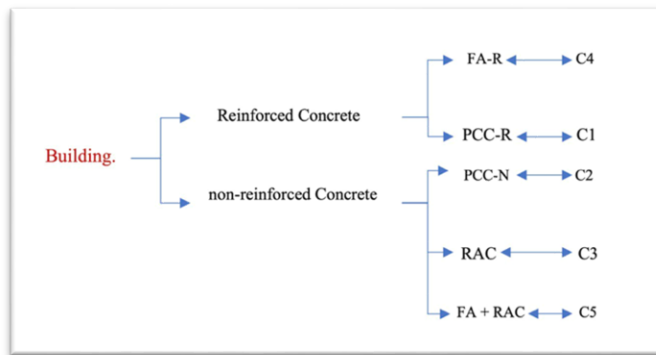


Figure 24. Classification and types of concrete materials used for different scenarios, (source author).

More details and investigation were needed, which led to more clarification on using GCM for the residential building sector. Therefore, Table 11 shows the classification of concrete types and scenarios in the

context of concrete code specification and components. In this regard, S1, S2, and S7 were selected as SD modeling and concrete types and scenarios classification examples to investigate CE principles and provide holistic insights into the construction process and the timeline for using recyclable materials, reducing and reusing.

Table 11 classified the quantity of concrete types and concrete scenarios.

Scenario s/ Concret e type	Scenario1 PCC-R & PCC-N		Scenario 2 PCC-R& RAC-N		Scenario 3 PCC-R&FA-N		Scenario 4 FA-R& RAC- N		Scenario 5 FA-R& FA-N		Scenario 6 PCC-R& FA-R & PCC-N			Scenario 7 PCC-R& FA-R& RAC-N		
Concrete quantity/ m3	CI 320	C2 162.2	C1 320	C3 162.2	C1 320	C5 162.2	C4 320	C3 162.2	C4 320	C5 162.2	CI 190	C4 130	C2 162. 2	CI 190	C4 130	C3 162.2
Strength	35 N	20 N	35 N	16 N	35 N	20 N	30 N	16 N	30 N	20N	35N	30N	20N	35N	30N	16 N

4.3.4.1. Modeling of the GCM Parameters

Investigate the (positive and negative) inner relations among the parameters, which help enhance the GCMs' selection. Therefore, the study demonstrates the creation of system dynamic models (SDM) at various levels and in various details. Vensim simulation software anticipates the model's performance over time. In this context, the SD approach estimates the changes and inner relations in the systems between different scenarios. GCM parameters are shown in Table 11.

4.3.5. Model Development

Based on the previous section, which is concerned with identifying the most critical variables and parameters for GCM, in this section, we added actual data for the residential project case study II, to integrate all together to investigate the role of selecting GCM for achieving CE and sustainability. First, based on the previous section. (2.3.1), which involves an in-depth analysis of previous research efforts on green material selection, including sustainability assessment, residential buildings, green building rating system, CE report, concrete code, and Egyptian residential regulation. Second, developed the conceptual framework for applying SDM and using GCM for CE transitions, focusing on recycled materials. This framework identified the sustainability benefits of using GCM, considering cement and natural aggregate consumption, strength, CO₂ emissions, waste generation, and cost-effectiveness.

4.3.5.1. The GCM for Achieve CE Principles

Therefore, using GCM, including recycled materials for partial cement replacement, such as by-product industrial and municipal waste such as FA and/or CDW, can cover several parameters for achieving sustainability. CE's core principles concern regenerative resources, long-life use, efficiency, and reuse of waste as a new source, which are considered when selecting GCM [123]. Thereby, RAC and FA can improve concrete utilization [86]. Most of these variables and parameters are linked with international and local residential green rating systems, such as the green building certification developed by the Building Research Establishment (BRE) in the United Kingdom and the Building Research Establishment Environmental Assessment Method

(BREEAM). Furthermore, Leadership in Energy and Environmental Design (LEED) is the US green building certification program, the Green Pyramids Rating System (GPRS) for sustainable building practices in Egypt, and the Egyptian residential concrete codes. Consequently, Table 12 presents the essential GCM variables. These variables and parameters help develop the framework for achieving GCM circularity.

Table. 12 The GCM variables and parameters help CE transitions

GCM Variables	Env	Eco	Tech	LEED	BREEM	GPRS
Waste management	✓			■	■	■
Reused raw material	✓			■		■
Recycled materials	✓			■	■	■
Durability			✓		■	■
Local Availability		✓		■		■
Resource efficiency	✓				■	
Cost effectiveness		✓				■
Carbon emissions	✓			■	■	■
Renewable materials	✓	✓		■		■
Hazard management	✓			■	■	
Site storage			✓	■		■
Prefabricated on site			✓			■
Maintainability			✓		■	■
Project cost		✓				■
Embodied Energy	✓				■	
Waste recycled on site			✓			■
Recycled aggregate	✓			■		
Minimize Pollution	✓				■	

- ✓ Refers to the sustainability aspects of GCM while (•) referring to the various green rating systems parameters.

4.3.5.2 The Description of Different and Constant Variables Values of GCM Scenarios

This research found that GCM value depends on chemical and physical properties and functions; therefore, constant and various variables were identified. Constant parameters that cannot change should be considered when

selecting substitution materials, such as durability, strength, and lifespan, which should be equivalent to PCC. In the same context, OPC's unit price is considered a constant in all scenarios obtained from local market prices for concrete materials. These variables are estimated based on government regulations such as Egyptian official building documents, concrete code specifications, and standards [203,204]. Various variables, including recyclability, availability, and maintainability, can be affected with natural resources, final cost, energy, waste, and CO₂ emissions) by different reduction rates. For example, data on the availability of local materials are collected from suppliers and residential project procurement. Meanwhile, the GCM quantity of the hypothetical scenarios is calculated based on the BOQ of the original project documents. The CO₂ estimation calculated is based on the cement production process and the (inventory of carbon and energy, ICE),[12],[14],[205],[206]. For more validity and accuracy, the concrete cost data is determined from the annual construction process cost, final construction project cost, and materials procurement, and the recyclable materials waste percentage is calculated based on the concrete code [204]. Furthermore, it was revised by third parties and supported by expert consultants' discussions in the construction industry.

4.3.5.3 The Conceptual Framework for Achieving GCMs Circularity Performance

The conceptual framework was developed based on the CE (10Rs) and GCM' selected parameters. It is considered an initial step and aims to examine GCM circularity using SDM based on the five stages [193]. In this research, the framework for selecting GCM in the construction process of residential building case study indicates the CE essential considerations for assessing the GCM's modeling initiative based on the quantities analysis of different hypothetical scenarios. The inputs and output expectations exemplify the optimum feedback between the process stages. Thereby, the framework helps as a crucial tool for investigating GCM' circularity by rejecting conventional materials, rethinking new and innovative solutions, redesigning for reducing consumption scenarios, followed by reselecting, replacing, reusing, and recycling purposes, and finally, recovery and redesigning new policies and regulations. Figure 25 describes the framework of CE transitions for selecting suitable GCM in the construction process of residential building projects.

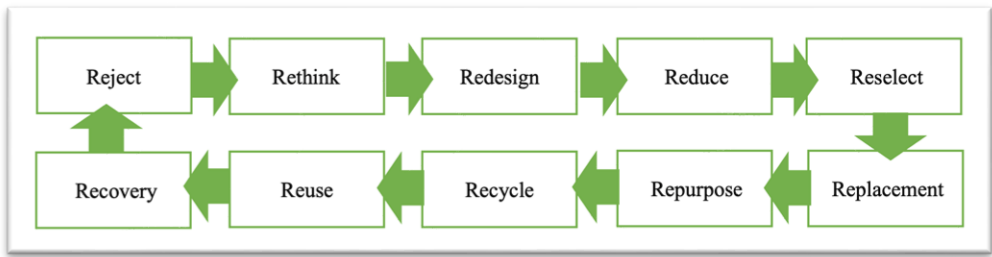


Figure 25. The conceptual framework of the SDM for GCM circularity transitions (source author).

4.3.6. The Causal Loop Diagram (CLD)

The current research created and developed a causal loop diagram (CLD) to visualize the feedback and demonstrate the SDM's structure. Additionally, it clarified how the dynamic interactions between variables can improve and influence the system and how the feedback loops in the dynamics system are determined. Consequently, the feedback loops that describe the different GCM scenarios and their dynamic behavior were investigated qualitatively. Figure 26 identifies the construction phase and the individual and group causal links of the residential building case study for achieving CE, thereby, sustainability. The CLD variables were selected based on GCM parameters, which were modified to suit the residential case study type and data. This allows the long-term investigation to be used for applying new policies for future residential construction projects.

In this regard, the study found that the positive feedback loops appeared in [R1-R2 -R3, R4], where the variables in the loops positively affect themselves, and any change in one variable will change another variable in the same direction. For example, the positive feedback loop R1 identified increases the CCM amount, increases project cement consumption and production, and increases embodied energy, thereby increasing CO₂ emissions and, finally, the concrete cost. This will increase the total final project cost and add to the total amount of CCM consumption. Figure 26 illustrates the details of the positive feedback loop (R1).

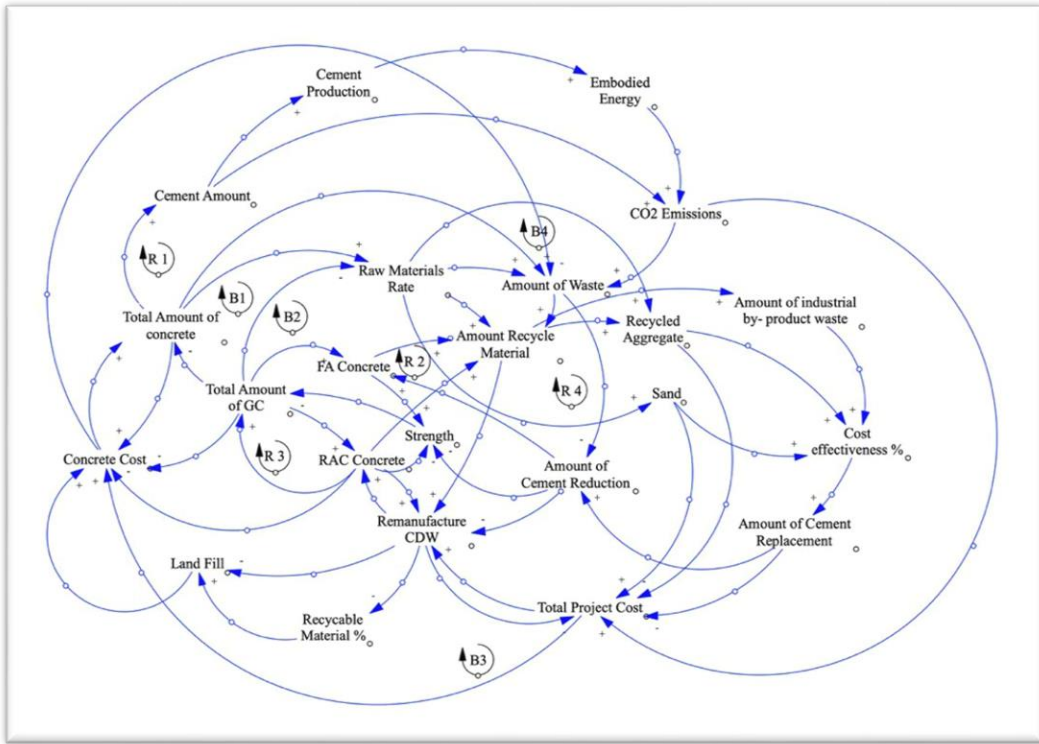


Figure 26. The green concrete material (GCM) causal loop diagrams (CLD) for achieving circular economy transition, (source author).

Furthermore, in the positive feedback loop R4, a significant waste increase indicates a decrease in the cement reduction strategy, a decrease in the CDW's remanufacture strategy, and a decrease in the total recyclable materials % rate. This increases the total amount of disposal to the landfill, increases concrete costs, and decreases the amount of waste. Eventually, an increase in the amount of concrete consumption will increase the concrete cost of residential building projects in the future, as shown in Figure 26, and apply the same context of the feedback loops R2 & R3.

On the other hand, the research found negative feedback loops in the loops [B1- B2- B3, B4], which are described as the following: in loop B1, noticed that there is a negative loop showing that any changes in variables in the causal loop; negatively affects the opposite direction. For example, the consumption of concrete increases the raw materials consumption rate, which leads to additional waste, increasing the opportunities for the number of recycled materials. This increases the CDW remanufacture strategy, and then additional RAC materials are added, which increases the total amount of GCM and then decreases the total

amount of CCM. Finally, reducing extra CCM leads to using more GCM in the project.

In the same context, the B2 loop shows that an increase in GCM usage will reduce the raw materials rate consumption and remanufacturing of CDW as a lower-strength RAC, which leads to a reduction in GCM usage in future projects. In Loop B3, we found that increases in total project cost caused an increase in concrete cost and consumption and an increase in recycled materials and recycled aggregate, which decreased the total project cost.

Whereas we found in the B4 loop, the amount of waste decreased in the cement reduction strategy, then a decrease in the CDW remanufacture strategy led to a decrease in the total recyclable materials rate. Consequently, increasing the total amount of waste disposed to the landfill reflects increasing the concrete cost, then decreasing the total amount of concrete, and finally decreasing the amount of waste. Clarifying the model's underlying assumptions is crucial before proceeding to the GCM-SF diagram to enhance its robustness and applicability. CE transition, the model's behavior variables should meet the core principles' needs, and each GCM scenario's effects were analyzed and handled in the same context.

4.3.7 The Stock and Flow Diagram (SF)

SF diagram identifies relationships among the various system components and is considered a central idea of dynamic theory by Sterman 2000 [193] due to its ability to map the stock and flow networks by using conceptual and mathematical definitions. Therefore, based on CLD, the SF diagram was created using Vensim software to clarify and identify the circularity between concrete materials' parameters during the thirty months of the construction process by 2022 and 2023. The typical SF diagram structure and its notation are followed, as noticed in Figure 27 based on Sterman, 2000 [149].

Stock and Flow Diagram General structure notation	
	
	Stock: is considered a state variable and noticed as a rectangle shape, which refers as containers of the stock.
	Flows: is the rate at which the stock is changing at any time and classified to inflows and outflows.
	Inflows: are appeared as a pipe (arrow) pointing into the stock (causing it to increase).
	Outflows: are represented as an arrow pointing out of the stock (causing it to decrease).
	Valves: control of flows, and drawn in the middle of flows.
	Clouds: showed both the sinks and sources of the flows. Which They are located outside of the model's boundary and they are used to prove that a stock is flowing from a source or into a source. Source: A source represents the stock from which a flow originating outside the boundary of the model arises; Sinks: represent the stocks into which flows leaving the model boundary drain.

Figure. 27. Stock and Flow Diagram notations [149],[193].

4.3.7.1 Model Boundary and Key Variable

First, the model boundary and key variables that affect GCM selection are defined. Table 13 describes the most significant variables in the SF diagram.

Second, the diagram was executed for the SD model by formulating the equations and using flow rate conjunctions to add to the stocks. Furthermore, the parameters were identified using the inputs and testing of structure and outputs to confirm the structure's ability to validate the behavior observed. Based on Table 13, which describes and identifies each parameter, the flow rates and stock combinations of simulating the SD mode are shown in Figure 28.

Table 13. The variables of the stock-flow (SF) diagram.

Abbreviation	Name of variables and description	Value	Unit
ANACM	Amount natural aggregate monthly	54.5	ton
ANA	Amount natural aggregate	1636.2	ton
ANARM	Natural aggregate reduction	298.5	ton
BFAM	Building floor area monthly	31	m ²
TCCM	Total amount concrete consumption monthly	16	m ³
TAC	Total amount concrete	482.16	m ³
TAOPC	Total amount OPC consumption	224.6	Ton
RAC	Recycled aggregate concrete	162.1	m ³
RCWR	Increase concrete waste recycle	80%	%
ICWR	Reduce concrete waste recycle	20%	%
TAOPCM	Total amount OPC consumption monthly	7.5	ton
TAS	Total amount sand	596.8	ton
TACA	Total amount coarse aggregate	1039.4	ton
ITACM	Increase total amount reduction cement monthly	0.5	%
TARCM	Total amount of reduction cement monthly	19.8%	%
DTARCM	Decrease total amount reduction cement monthly	20.5	%
ITARCM	increase total amount reduction cement monthly	0.5	%
ACMWM	Amount concrete material waste monthly	0.3	%
TACMW	Total Amount of concrete material waste	10	%
PCCS1	Reduction cement cost S1	0.0	LE
PCCS2	Reduction cement cost S2	47,066	LE
PCCS3	Reduction cement cost S7	89,890	LE
TCC	Total concrete cost	2,117,1	LE
TCCM	Total concrete cost monthly	70,570.2	LE
UCOPCM	Unit cost OPC monthly	15,123.0	LE
COPC	Cost OPC	453,6913	LE
TARCC	Total amount reduction cement cost	136,95.6	LE
VROPCCS1	Value reduction OPC cost S1	00.0	%
VROPCCS2	Value reduction OPC cost S2	10.4	%
VROPCCS3	Value reduction OPC cost S7	19.6	%
OPCCS1	OPC cost S1	453,691.3	LE
OPCCS2	OPC cost S2	406,683.4	LE
OPCCS3	OPC cost S7	363,804.6	LE

Table 13.(continue) The variables of the stock-flow (SF) diagram.

Abbreviation	Name of variables and description	Value	Unit
OPCCS1M	OPC cost S1 monthly	15,123.0	LE
OPCCS2M	OPC cost S2 monthly	13,556.0	LE
OPCCS3M	OPC cost S7 monthly	32,646.0	LE
TFA-NM	Total Fly ash – non-reinforced monthly	0.63	ton
FA-N	Fly ash – non-reinforced concrete	162.16	m ³
IPCRFA-N	Industrial product cement replacement fly ash non reinforced	30%	%
TPCC-NM	Total Portland concrete- non reinforced monthly	1.68	ton
TPCC-N/M	Total Portland concrete- reinforced monthly	5.8	ton
TRAC-NR/M	Total recycled aggregate concrete- non reinforced monthly	0.9	ton
TFA-R/M	Total flay ash - reinforced monthly	4.1	ton
PCC-N	Portland concrete- non reinforced	162.16	m ³
PCC-R	Portland concrete- reinforced	320	m ³
RAC-N	Recycled aggregate concrete- non reinforced	162.16	m ³
FA-R	Fly ash – reinforced concrete	320	m ³
PCC-NHC	Portland concrete-non reinforced high consumption cement	162.16	m ³
PCC-R/HC	Portland concrete- reinforced high consumption cement	320	m ³
RAC-N/HR	Recycled aggregate concrete- non reinforced high recyclable	63.3	%
IPCR/FA-R	Industrial product cement replacement fly ash- reinforced %	30%	%
TCO ₂	Total CO ₂ emission reduction	34.9	ton
CO ₂ M	CO ₂ emission monthly	5.9	ton

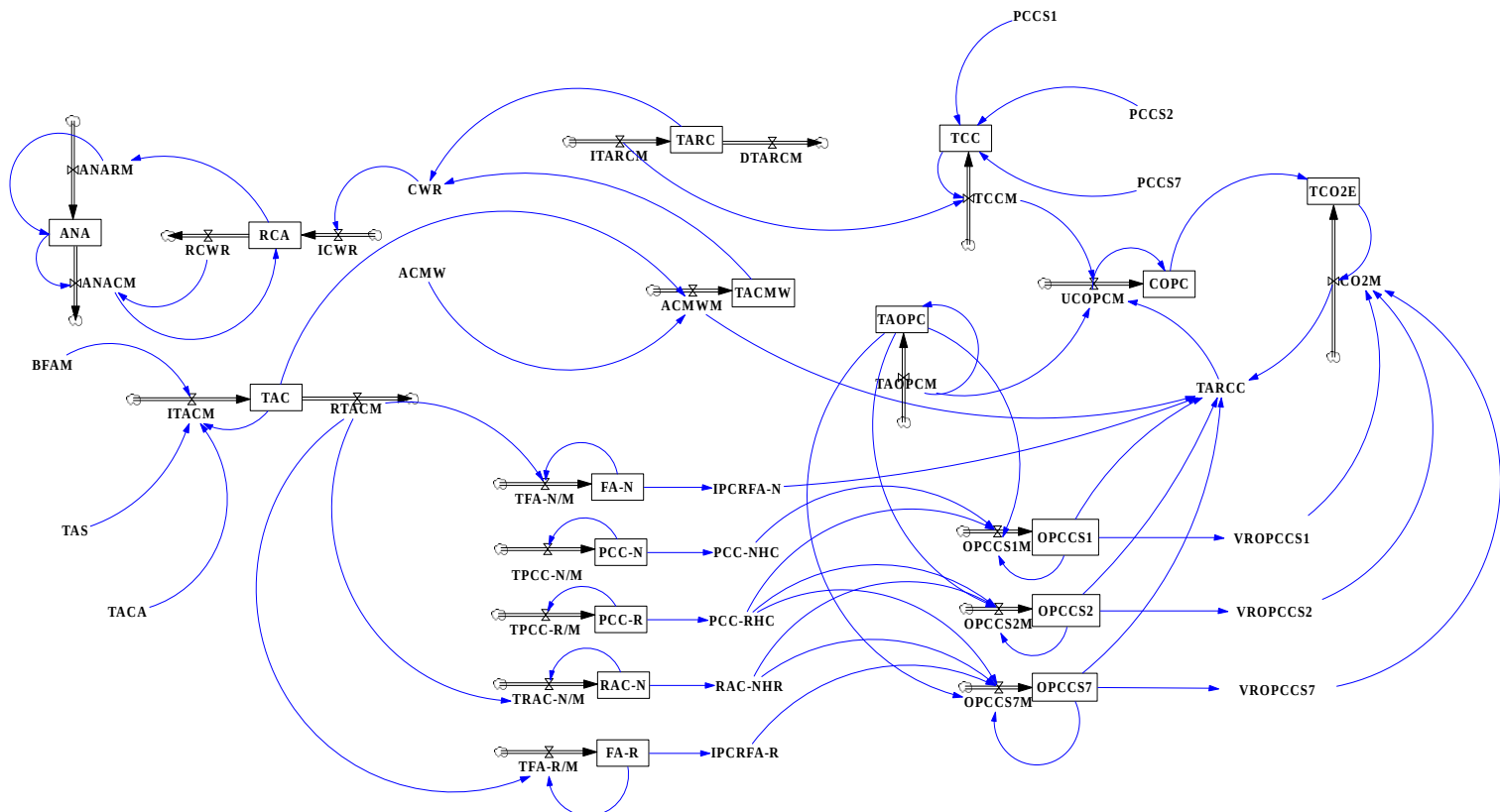


Figure 28. The Stock and Flow Diagram (Source author).

All the key variables that affect the use of GCM in residential buildings were identified as related to the CLD and converted to an SF diagram using VENSIM software, as shown in Figure 28. All the construction process of the building case study II variables are described and quoted in detail, based on Table 13.

4.3.8 System Dynamic Model

4.3.8.1. The GCM Simulation Process

Each variable is assigned as a value to allow for quantitative analysis based on calculating and estimating the essential variable value from a case study of the real residential project, considering the government residential building rules and regulations in the same urban context, and revised with third-party consultancy to ensure the validity of model parameters and equations in the proposed SD model. The developed model provided input values for specific parameters to run the simulation. This ensures the model accurately represents the actual environment before running the simulation [136],[207].

The GCM simulation process was applied after identifying the parameters that needed value input to run the simulation. For example, the simulation results investigated cement, natural aggregate, waste reduction rate, CO₂ emissions, and concrete cost for an exciting building case study (2) for the structural and non-structural works based on the project timeline for the construction process phase.

4.3.8.2. The Cement Consumption for Different Concrete Types Scenarios

The results showed that the cement consumption in different concrete types is as follows: Cement test 1: the total PCC-R per month (TPCC-R/M) showed the highest monthly cement consumption, followed by the total FA-R monthly (TFA-R/M), the total PCC-N monthly (TPCC-N/M), the total RAC-Monthly (TRAC-N/M), and the total FA-N monthly (TFA-N/M), respectively. Figure 29 illustrates test 1, the simulation result of cement consumption in various concrete types used in scenarios S2 and S7.

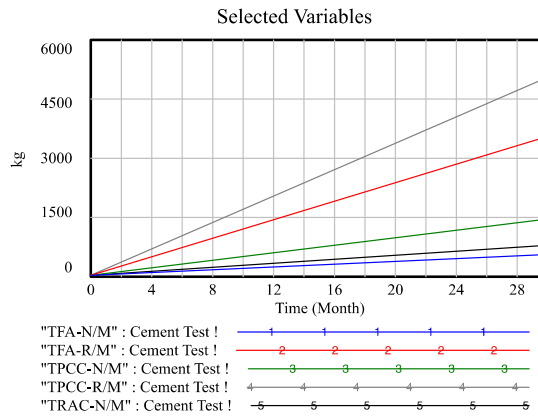


Figure 29. The Cement consumption in various concrete types

Cement test 2: examined the waste consumption as industrial and municipal waste in the form of (FA and RAC) for cement replacement. The result showed in Figure 30 that the variable as [industrial product cement replacement FA-reinforced per month (IPCFFA-R/M)] is higher than [recycled aggregate concrete-non-reinforced high recyclable (RAC-NHR)], and [industrial product cement replacement fly ash- nonreinforced (IPCRFA-N)] has no consumption, due to its usage limitation.

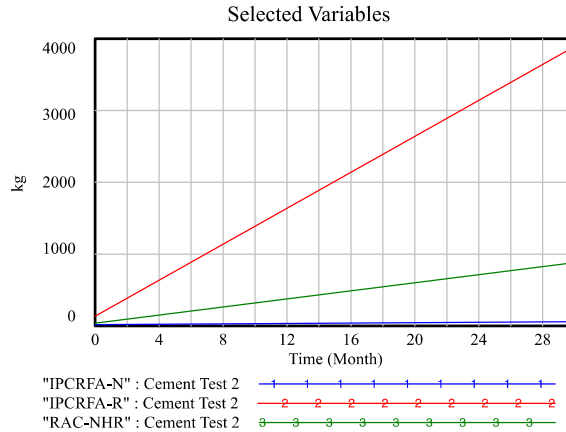


Figure 30. Cement replacement by using industrial and municipal waste and recycled aggregate consumption.

4.3.8.3. Natural Aggregate (NA) and Recyclable Materials

In test 1, the simulation result showed the relation between the [amount of natural aggregate consumption monthly (ANACM)] and the [amount of natural aggregate reduction monthly (ANARM)] after applying the reduction strategy

and using RA. Additionally, the relation of [increased the total amount of concrete monthly (ITACM)] and [reduced total amount of concrete monthly (RTACM)], with the [total amount of coarse aggregate (TACA)] and the [total amount of sand (TAS)]. Figure 31 illustrates the natural aggregate test1.

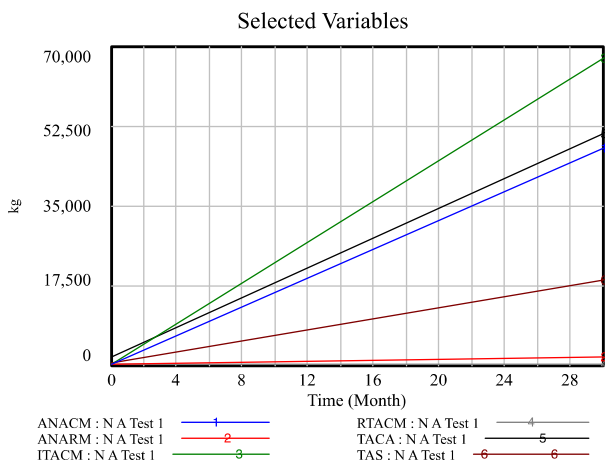


Figure 31. The simulation result of the amount of NA and concrete consumption and reduction of monthly.

Test 2: Figure 32 shows the relation between concrete types with recyclable materials. The [total FA-R monthly (TFA-R/M)] is the most concrete type that has a recyclable materials quantity, followed by the [total RAC non-reinforced monthly (TRAC-N/M)], and the [total FA non-reinforced monthly (TFA-N/M)], and noticed that there is no effect on [reduction total concrete consumption, (RTACM)], due to, it was considered as a constant variable.

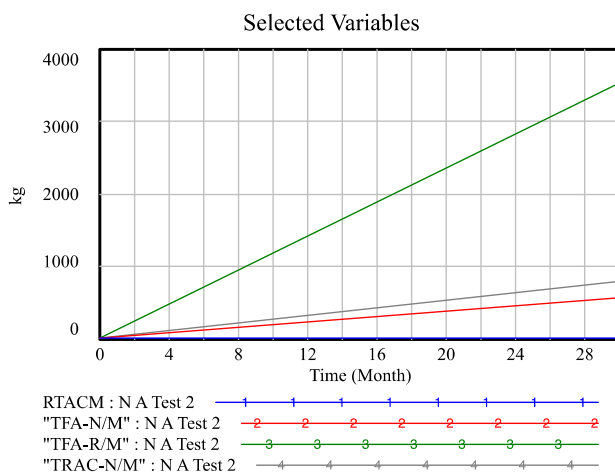


Figure 32. Simulation results for the total amount of three concrete types monthly usage recycled materials.

4.3.8.4. The CO₂ Emissions in Different Concrete Types

In this section, the CO₂ emission estimated based on the calculation using CDIAC's method, which is concerned with the cement production OPC type, considered that one ton of cement produced $0.136 \times 3.667 = 0.50$ tons of CO₂ reported by (Andrew 2019; Marey et al. 2022, 2024; Yang et al. 2015c). In this regard, the simulation illustrates the highest CO₂ emissions per month for different GCM types. Therefore, the value of CO₂ reduction based on the OPC quantity reduction started from the concrete type FA-N>RAC-N >PCC-N >FA-R >FA-N compared to the OPC quantity of concrete S1, which is considered a high CO₂ producer as referred by CO₂M shown in Figure 33.

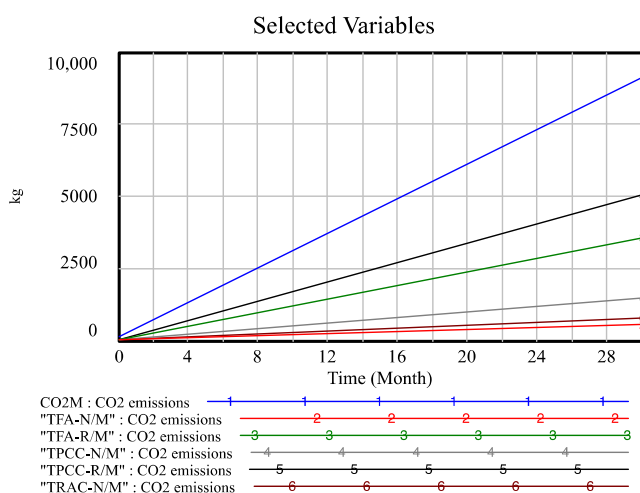


Figure 33. Simulation results for CO₂ emissions for OPC cement production.

4.3.8.5. The Construction Waste Reduction Amount and Different Concrete Types

As noticed in Figure 34, the relation between the total [amount rate of concrete materials waste monthly (ACMWM)] caused for [increased the concrete waste recycling (ICWR)] rate and [reduced concrete waste recycling (RCWR)] rate. Moreover, the relations are identified between the rates of [decreased and increased total amount of reduction cement monthly (DTARCM)] and [increase the total amount of reduction cement monthly (ITARCM)] over time. Consequently, this indicates that the project's overall amount of concrete waste reduction is still marginal. Meanwhile, it shows a lack of applied circularity and poor implementation of waste regulations in residential projects. Thus, the most

optimum and fundamental solution for reducing the total amount of waste is to apply on-site sustainable waste management and improve waste regulations by increasing the recycling, remanufacturing, and reusing strategies for concrete waste, then reducing waste generation and eliminating illegal dumping of CDW in landfills [46],[209].

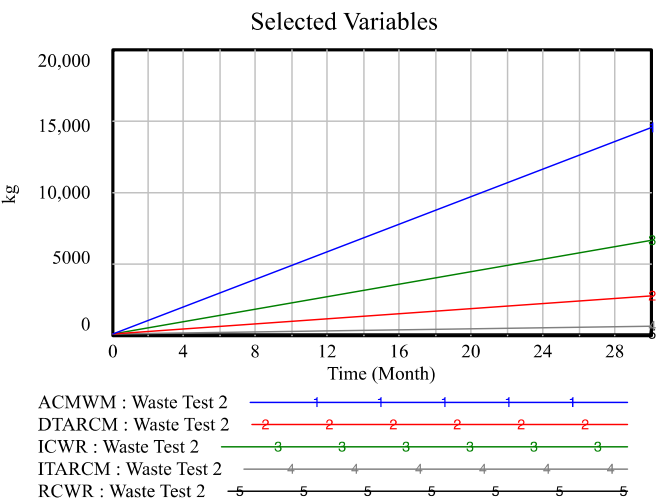


Figure 34. Simulation results for identifying concrete waste's increase and decrease.

4.3.8.6. The Cost-Effectiveness of Different Concrete Types

In this dissertation, the cost of the three types of concrete identified depends on the cement and supplementary materials, natural aggregate, and recycled aggregate. The cost is limited to several aspects of OPC and supplementary cementitious materials such as FA and RAC. For example, the cement cost of scenario S7 increases by 76% compared with the cement cost of scenario S1. Meanwhile, the cement cost of scenario S2 is the lowest price, and the total cost decreased by 16.6%. In Figure 35, the simulation results show that the relation between the cement and OPC cost of scenarios is ordered as OPCCS7M > OPCCS1M > OPCCS2M.

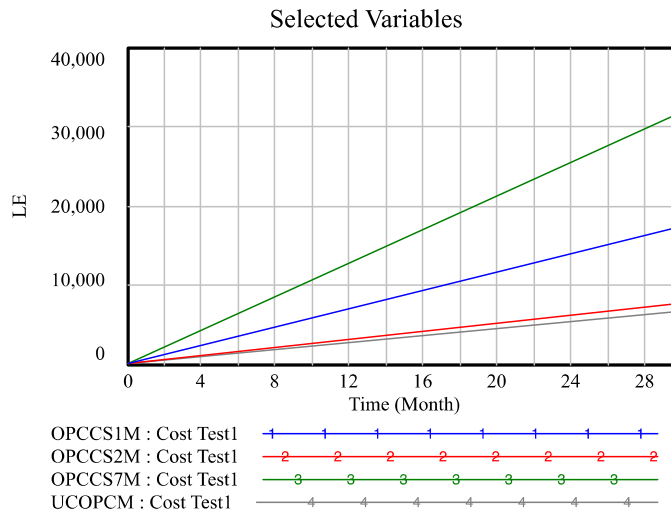


Figure 35. The amount of OPC cost for three scenarios: S1, S2, and S7.

4.3.9 Concrete Scenarios Analysis

4.3.9.1 The Effects of Using GCM for Achieving CE

However, this study aims to identify the parameters that affect GCM selection in the context of CE principles. Therefore, investigating and analyzing the previous scenarios to select the most optimum one suitable for achieving CE in the construction of residential buildings occurred based on considering the SI as a base- scenario and the other six as hypothetical scenarios. The simulation showed how various scenarios could influence CE principles, like cement consumption, CO₂ emissions, natural aggregate, waste reduction, and materials cost. As shown in Table 14, the benefits of using different concrete scenarios led to selecting the most optimum scenario, highlighting the three selected scenarios. Table 7. identified the total concrete quantity for the building case study drawing and dimensions.

The result showed the OPC percentage in seven scenarios in CCM and GCM (RAC&FA). The cement reduction reached 19.8% and 11.4% (S7&S2) in the most optimum scenarios, as a follow, started with full ratio cement consumption of 100% in the CCM as an S1, followed by [S2 by 89.6 %, S3 by 86%, S4 by 66.37%, S5 by 62.75%, S6 by 90.55%, and S7 by 80.19%]. The total amount of cement per ton used to estimate the cost in the six hypothetical

scenarios is 89.6%, 86%, 66.37, 62.75, 90.55%, and 80.19 %, from [S2, ..., S7] respectively.

On the other hand, the reduction of NA started after using recycled materials, reaching the most reduction by 19.1% in S2, S4, and S7. The lowest consumption level reached approximately 81%, amounting to 842.1 tons, followed by S3 and S5, which reached 83%, amounting to 863.7 tons, compared with S1 and S6, which consumed 100%, amounting to 1039.5 tons, which is the original NCA amount in the reference scenario.

This result promotes variety, which adds more evidence for controlling the consumption of cement and NA. Consequently, it reflects that there is a high ability to apply GCM and achieve circularity in the residential sector. Furthermore, it provides insights into GCM selection to investigate their suitability for reducing, reusing, and recyclability of the total quantity of concrete components. Table 14. The benefits of using GCM circularity in cement include reduction of CO₂ emissions, natural aggregate, and cost-effectiveness.

Table 14. The benefits of using GCM circularity in cement reduction CO₂ emissions, Natural aggregate, and cost-effectiveness.

Concert	Senario1		Scenario 2		Scenario 3		Scenario 4		Senario5		Scenario 6			Scenario 7		
Concrete Type	PCC-R	PCC-N	PCC-R	RAC-N	PCC-R	FA-N	FA-R	RAC-N	FA-R	FA-N	PCC-R	FA-R	PCC-N	PCC-R	FA-R	RAC-N
Concrete ratio	1:1:2	1:2:4	1:1:2	1:4:8	1:1:2	0.3:0.7:4:8	0.3:0.7:1:2	1:4:8	0.3:0.7:1:2	0.3:0.7:4:8	1:1:2	0.3:0.7:1:2	1:2:4	1:1:2	0.3:0.7:1:2	1:4:8
Cement amount /ton.	174.2	50.4	174.2	27.2	174.2	19	121.9	27.2	121.9	19	103.4	49.5	50.4	103.4	49.5	27.2
Total Cement/ ton	224.6		201.4		193.2		149.1		140.9		203.3				180.1	
Cement/ bag	4492.0		4026.6		3863.6		2981.5		2818.6		4067.5				3602	
Cements %	100 %		89.6 %		86 %		66.37 %		62.75 %		90.55 %				80.19 %	
t CO ₂	176.3		158		151.7		117		110.6		159.7				141.4	
Sand /ton	378	219	378	118	378	118	378	118	378	118	224.4	154	219	224.4	154	118
Sand/ ton	597		496		496		496		496		597.4				496.8	
Sand %	100 %		83.1 %		83.1 %		83.1 %		83.1 %		100 %				83.1 %	
Aggregate/ton	658.3	381.2	658.4	185	658.4	205.3	658.4	185	658.4	205.3	391	268	381.3	391	268	185
NCA/ ton	1039.5		843.4		863.7		843.4		863.7		1040.3				844	
NCA %	100 %		81 %		83 %		81 %		83 %		100 %				81 %	
Cement Cost/LE	351,826	101,865	351,826	54,857	351,826	274,664	1,028,872	54,857	1,028,872	274,664	208,896	715,633	101,865	208,896	715,633	54,857
	453,691		406,683		626,490		1,083,729		1,303,536		1,026,394				979,386	

4.3.10 The Circularity and Sustainability Performance of the GCMs Optimum Scenarios

The study found that applying GCM's circularity performance by selecting the most optimum scenarios can enhance the construction sector's sustainability performance. The CE 10R principles can realize sustainable concrete materials for construction and suitable residential buildings. Figure 36 illustrates and summarizes the 10Rs CE principles for the optimum five concrete scenarios. The process started with rejecting CCM and massive natural resource consumption by refusing the use of materials and products that harm the environment. This allows for redesigning, rethinking, and reselecting innovative GCMs [24],[130]. Furthermore, reducing negative environmental impacts by substituting recycled materials that can be applied easily when the GCM meets the same strength and durability [128],[140]. Meanwhile, replacement and repurposing are crucial in recycling and reusing the waste as new material sources, such as RAC and FA [82],[94],[95],[201]. This will enable redesigning new policies and regulations that enhance and recover natural resources and reduce the waste stream for concrete materials during their life cycle.

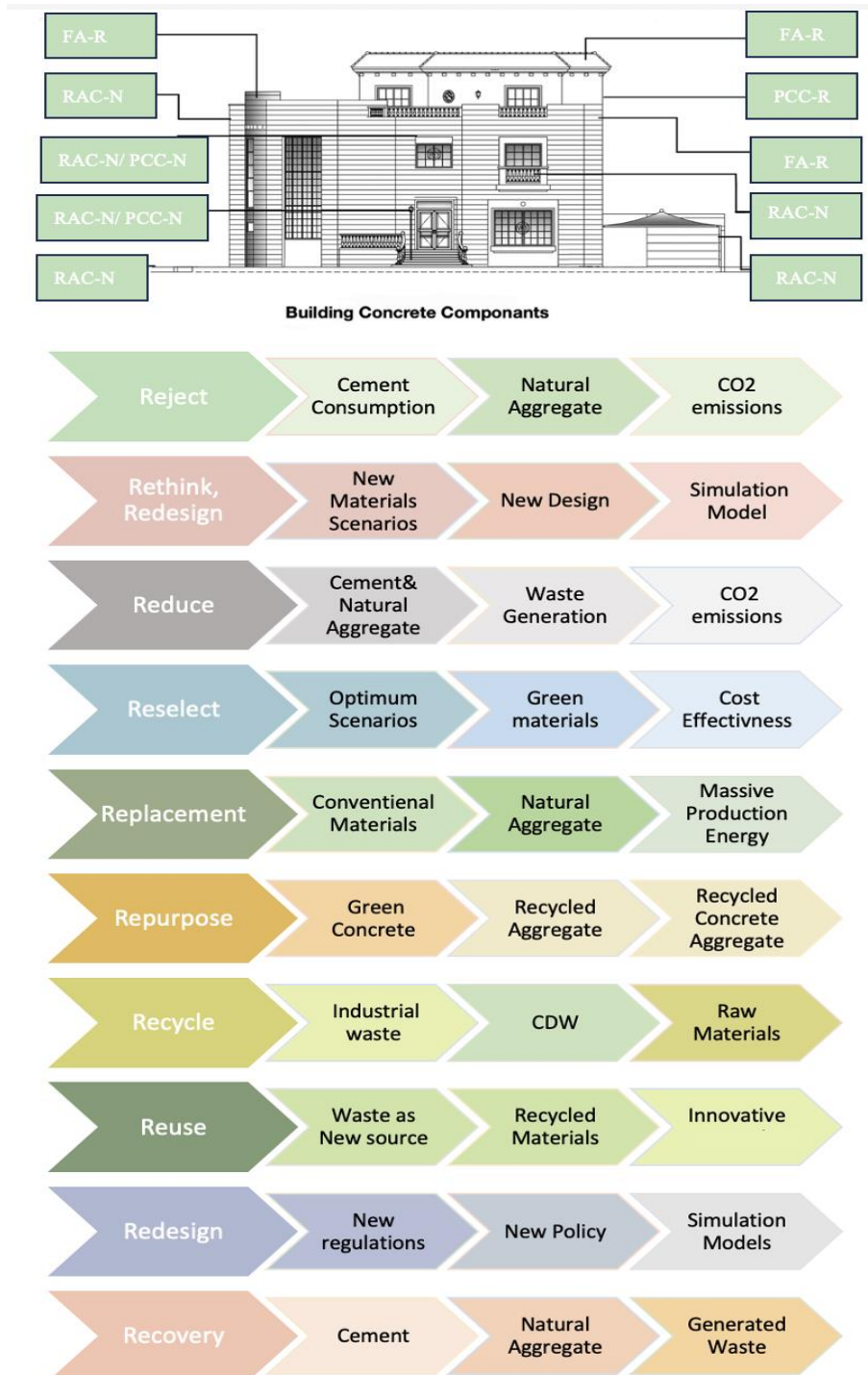


Figure 36. The 10Rs CE principles for using GC in the construction process of residential buildings (source author).

4.4. Green Concrete Materials Sustainability Framework

However, applying sustainability performance by using GCM in residential buildings still faces challenges, which require more investigation that can help professional organizations in the public and private sectors apply new policies, residential regulations, and technical standards. Therefore, this dissertation's empirical practices promote opportunities for using and selecting GCM, which is considered a first attempt and presents a great chance for insight look and further investigation. In this regard, developing a GCM sustainability framework to address the construction sector challenges from the perspectives of environmental scientists, engineers, and designers became crucial. Thus, the GCM data and information in this section are introduced based on a holistic approach consistent with the residential buildings' requirements for quantifying the GCM-SI based on the previous building case studies and the global sustainability perspective, such as CE, SDGs, and sustainability pillars, which introduced in the previous section in Chapter 2. This step attempts to unify the GCM sustainability potential framework, promoting a comprehensive and holistic outlook for using GCM in residential buildings. Furthermore, clarifying the indicators at a specific scale, such as the residential sector, will enable a more extensive sustainability analysis and definition of the most important priorities for GCM. Additionally, the framework considers the first call of action in the Egyptian residential building, which will illuminate GCM's contributions toward realizing the UN 2030 sustainability agenda.

4.4.1. The Residential Building Construction Features for Using GCM

Therefore, the residential sector sustainability indicators are identified based on the previous sections' literature and research case studies,[24],[44],[203],[210],[211],[212],[213],[214],[215]. We found that using GCM is increasingly important and has a wide impact on environmental, economic, and social aspects, especially in residential projects, to reduce natural resource consumption, negative environmental impact (CO₂ and waste), cost-effectiveness, and promoted occupants' comfort level, due to the following factors:

- The number of residential buildings has increased in recent decades, encouraging the use of alternative green materials and sustainable solutions [18],[59].

- Residential features focus on building aesthetics, property value, floor size, load requirements, occupants' comfort level, durability, budget constraints, building regulations, and customization, which are considered when selecting GCM for constructing residential projects,
- The variety of GCM types and strategies are suitable for residential building materials characteristics and design compared with other building typologies [97],[216]. This leads to more investigation into using several types of GCM as a sustainable practice for various building parts.
- GCM offered ideal residential-use materials due to their functionalities and versatility for achieving sustainability [24],[95],[217].
- The GCM choice in the construction process of residential buildings involves homeowners' preferences, especially for including various finishes in colors and textures.
- The residential building often requires comfortable and flexible interior spaces to accommodate different lifestyles, which results in the use of GCM for interior purposes and finishes, such as decorative elements.
- It was found that the total concrete quantity used in residential construction is typically less, but the quality and surface finishing are often emphasized.
- Durability is crucial for all residential building types, and the aesthetics of concrete surfaces have the same priority.
- GCM supports the loads associated with the structure, for instance, in the case of the current research case studies, they have lower load requirements than other building typologies, such as commercial and industrial, which are suitable for using GCM and can influence the project in the design and construction phases.
- Sustainable residential building specifications require specific thermal and acoustic properties to enhance comfort. Therefore, specific types of GCM, commonly used in residential buildings, play an insulating and soundproofing role.
- Budget limitations can affect the choice of concrete materials and the selection of the most cost-effective solutions that meet quality and aesthetic expectations.
- Maintenance costs for GCM are very important, homeowners usually prefer lower-maintenance materials.
- Local availability and transportation are important for increasing the use of GCM; therefore, the materials that have the local recycled waste materials of their component are considered the most optimum solution, such as RAC, which is made from recycled CDW from the same and nearest construction site.

4.4.2. Green Concrete Materials (GCM) Strategies and Types for Residential Building

The current research has investigated the GCM's suitability for residential buildings and found that the most common and eco-friendly concrete strategies focus on energy and resource efficiency by reducing low-primary energy use and using sustainable alternative materials and chemical admixtures [21]. In this regard, partial replacement with SCMs, such as FA and RAC, is used as by-product manufacturing waste and municipal waste [184],[21],[107],[218].

In the meantime, these materials can be used in low-rise buildings, providing the same durability and strength as CCM, even used for structural and/or non-structural works considering reinforced and non-reinforced concrete on various building parts [21],[219]. This is because GCM has a wide variety of types regarding their mechanical properties, compressive strength, durability, and workability, which promotes the material's broad use with different strategies, considering the residential buildings codes and regulations [220],[221].

We found that the use of GCM in residential buildings should be considered during the building's lifespan, from the early design stage until demolition and materials disposal at landfills [222],[223],[224],[225].

4.4.3. The Relation Between the GCM and the Three Sustainability Pillars

The current section discussed the relationship between the GCM and the three bottom pillars of sustainability. The study found that using GCM for residential buildings requires 36 indicators based on previous case studies, LR, Egyptian building code, concrete code, and international and national green building rating systems such as the Green Pyramids Rating System (GPRS) [203],[7],[66],[167],[172],[186],[226],[227],[228],[229]. For example, the environmental indicators are focused on reducing CO₂ emissions, waste generation, natural resource consumption, pollution, and energy use. Meanwhile, the economic indicators are concerned with monetary aspects, like final project cost, property value, maintenance, and material cost; furthermore, the cost of production processes, transportation cost, local availability, building methods, and technology. However, many indicators concern regional and geographical features and are always measured with the limitations and constraints of concrete codes and building type regulations, but there are indicators classified as global standards. Figure 37 presents the GCM sustainability indicators based on the sustainability pillars and dimensions.

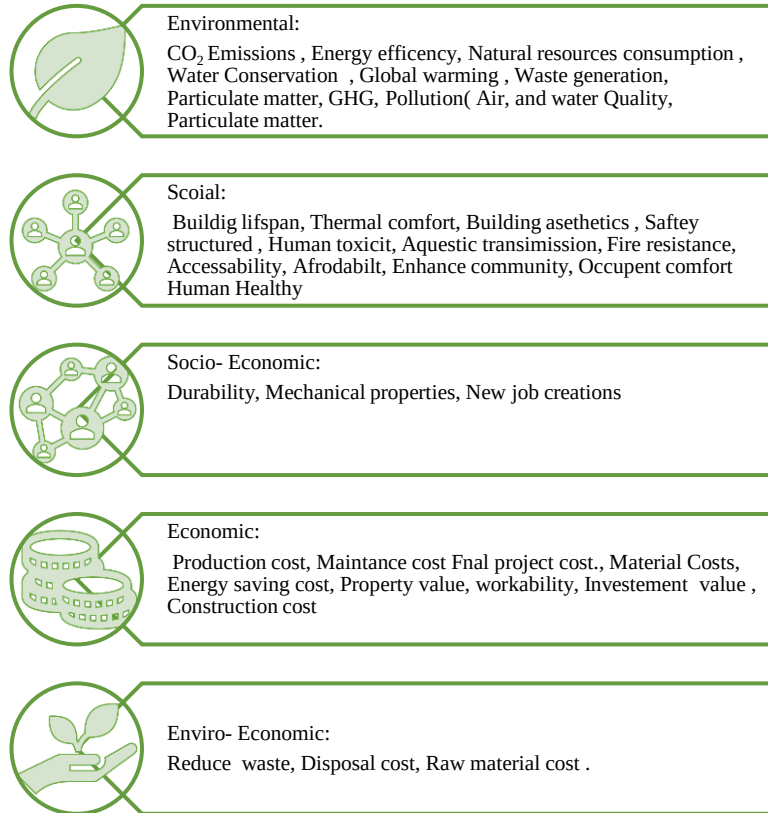


Figure 37. The GCM sustainability indicators are distributed with sustainability dimensions for residential buildings (source author).

The study found several indicators have a multidimensional contribution, realizing more than one sustainability pillar. Consequently, the distribution of the GCM indicators for use in the residential building reflects the economic, social, and environmental sustainability pillars by 33%, 27%, and 24%, respectively, as shown in Figure 38. However, many indicators are aligned between two pillars, such as the social-economic (Soc-Eco) and the Social Environment (Soc-Env), with 8%. For example, the GCM's durability and strength have contributed to Soc-Eco indicators by affecting property costs, new markets, and new jobs. Meanwhile, Soc-Env is aligned with the disposal and recycled material costs.

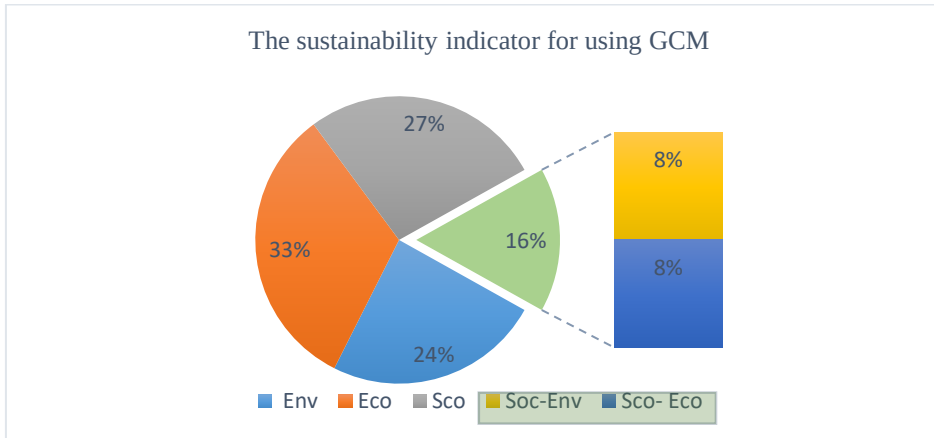


Figure 38. The distribution of the GCM indicators and three sustainability dimensions.

4.4.4. The GCM- SI for achieving SDGs

The benefits of applying GCM in the residential sector increase the importance of investigating their contribution to achieving sustainable development [175],[230]. The integration of sustainability perspectives, CE, three pillars, and SDGs provides a solid context for examining the GCM that can embody the goals of SD. Therefore, selecting the indicators with strong linkages and balancing the three pillars aims to validate the final selection. Consequently, the linkage of each pillar and indicator is identified to trace its causality relationship [231],[162],[194]. In this regard, we narrowed the indicators to 27 selected in the analysis, whereas each pillar contributed 9 of GCM-SI. We found that each GCM-SI has a different contribution and score level with SDGs; thereby, we focused on high and low contributions only by applying multicriteria analysis. Therefore, the 27 GCM-SI are identified and combined by (weighted sum) based on an indicator-based assessment approach for GCM sustainability evaluation.

Therefore, the evaluation was applied by using equal weights for sustainable indicators ($SI_w = 1.000$) for more simplicity and dimensional equality. Thereby, the GCM-SI weights were calculated by using the following expression:

$$W_i = SI_w / N$$

Meanwhile, the W_i : GCM-SI weight, SI_w weight assigned per SDGs, and N number of GCM-SI and SDG contributions (high or low). “For instance, in the

weighting process for high levels (including high and very high) in the environmental pillar and SDG1, the GHG indicator was assigned with $(W_i) = 0.22$ since $(N) = 9$ and participation of $(SI_w) = 2$.

4.4.5. Green Concrete Material Sustainability Indicators (GCM-SI) for Achieving Sustainable Development Goals SDGs

Considering SDGs as a structured basis, GCM-SI can be defined and distinguish between their differences and similarities by identifying the contributions between the 17 goals and their targets, as well as the sustainability performance [94],[183],[219],[226],[232],[234],[235],[236],[237],[238].

The SDGs network for using GCM in the residential building sector is identified based on the proposed framework by Le Blanc [190], which was concerned with identifying the link and relation between SDGs and their targets. Therefore, the assessment was accrued by identifying GCM-SI based on two global sustainability perspectives (SDGs and three sustainability pillars) [164],[195]. Primary and specific indicators are investigated, such as CO₂ emissions, energy efficiency, raw materials consumption, recycled materials usage, waste generation, pollution, and building lifespan. Additionally, the indicators are proven based on case studies 1 and 2, methods for assessing and investigating the GCM types, and strategies, which prove their suitability for achieving sustainable benefits for residential building projects. The study found that using GCM for residential buildings is linked to SDGs, but it is necessary to investigate the comprehensive classifications of these indicators and understand the direct and indirect sustainability relationship.

4.4.6. The Sustainability Framework for GCM-SI Contribution to the Pillars and SDGs

This section investigates the contribution of the SDGs, sustainability's three pillars, and GCM-SI and identifies in detail. We found that using GCM can be vital in realizing the SDGs. The results showed potential effects in reducing environmental, economic, and social challenges, especially for residential projects. Table 15 identifies in detail the indicators and their contribution level for the SDGs and pillars.

4.4.7. The GCM-SI High Contribution

The study found that GCM-SI’s high contribution level strongly contributes to achieving several SDG goals. As shown in Figure 39, SDG6 and SDG12 have the highest environmental contributions [43]. While in the economic pillar the contribution with “SDG3, SDG8, SDG9, SDG11, and SDG12”, and social pillar is contributed to “SDG5, SDG9, SDG11, and SDG12” within the highest level. Consequently, these high-level goals indicated that indicators significantly contribute to SDGs. Furthermore, it is indicated that using GCM for the residential sector faces may face challenges if the SDGs and sustainability pillars are not considered as a whole strategy.

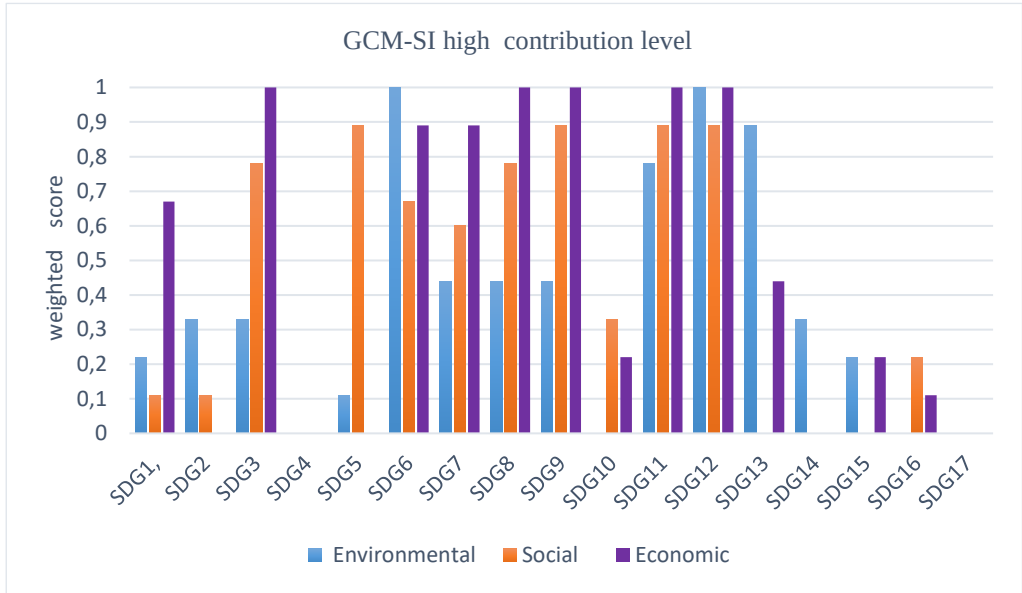


Figure 39. The high level of the contribution between the SDGs, environmental, social, and economic pillars, and GCM-SI.

4.4.8. The GCM-SI Low Contribution

However, the identified contribution by light and dark yellow (see in the previous section) is referred to as low and very low levels. The result showed that these indicators contributed to environmental, social, and economic through (SDG4, SDG10, SDG16), (SDG14, SDG1, SDG2, SDG16), and (SDG4, SDG5, SDG14, SDG15, SDG16) respectively. Thus, these indicators have an obstacle, which needs more investigation in future research efforts and support within new rules and regulations for the future residential projects and concrete market. As

noticed in Figure 40 the high value indicates that these indicators have a low contribution to the SDGs.

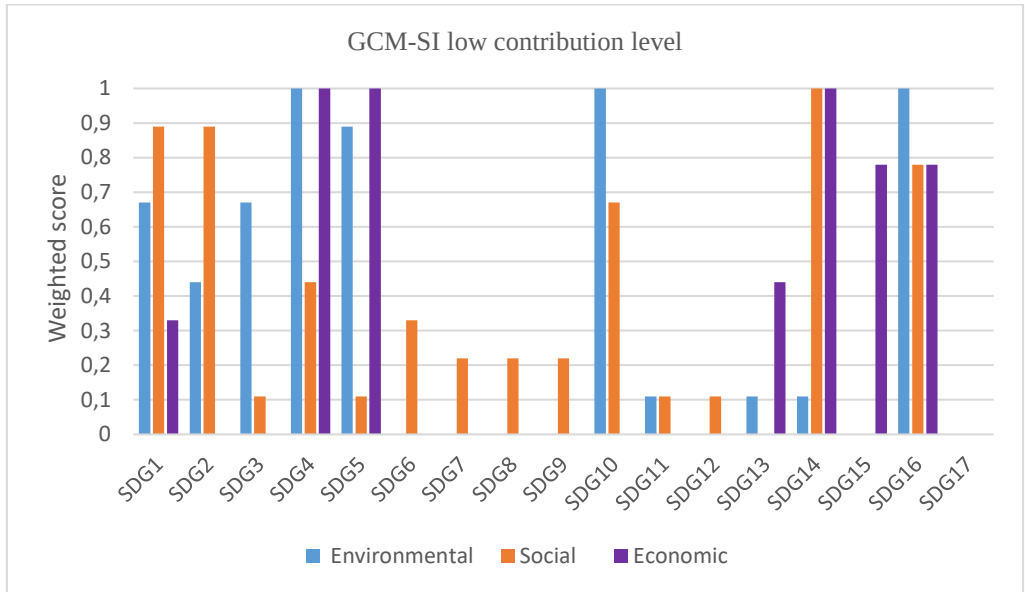


Figure 40. Low-level contribution for GCM-SI. through the SDGs and pillars.

4.4.9. The most GCM-SI contributed to achieving SDGs

Therefore, this section identified the overall high relation between the GCM-SI and SDGs through the sustainability pillars. Figure 41 clarifies the distribution of the high and very high contribution levels between the GCM-SI and the SDGs. The previous levels were clarified by considering SDG17's constant goal with all three pillars. The study found that 13 goals contributed to the high and very high levels between GCM and the environmental pillar, and 12 are in both the social and economic pillars. Figures A1, A2, and A3 in the appendix present the GCM-SI contribution within three sustainability pillars (environmental, economic, and social) and the SDGs based on the five-point scale identified previously in the section.

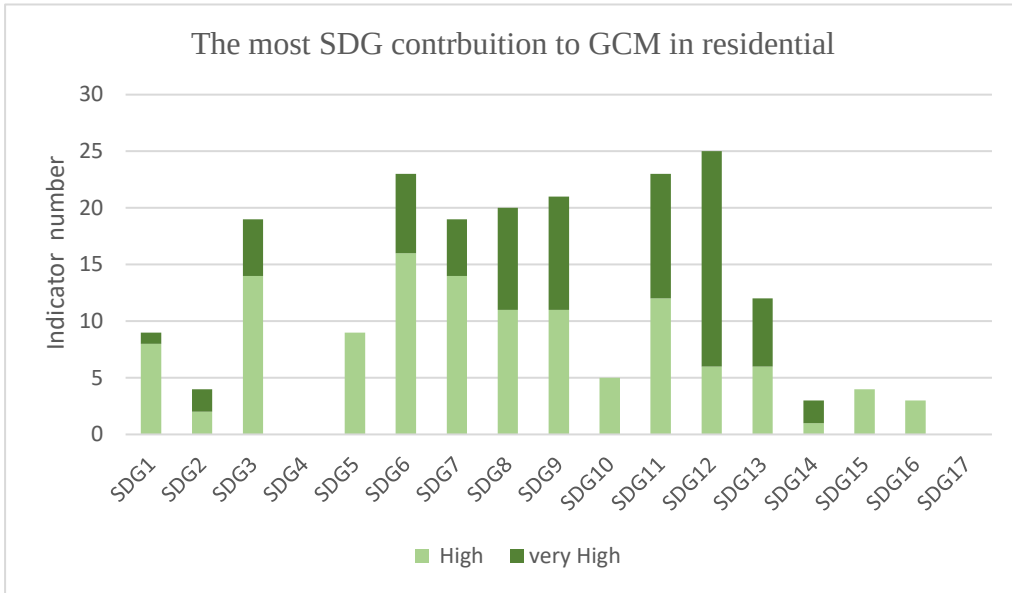


Figure 41. Most GCM-SI and SDG contribute through the sustainability pillars to high and very high levels.

In the same context, for more investigation of high-level contributions, which consist of (high level – very high level), we found that using GCM in residential buildings strongly contributes to SDGs. Figure 42. shows the high contribution to SDGs of 92%, 85%, 77%, 74%, and 70% in SDG12, (SDG11, SDG6), SDG9, SDG7, and (SDG3, SDG7) respectively. Furthermore, scored 44%, 33%, 18%, 14%, 11%, within the SDG13, (SDG1, SDG5), SDG10, (SDG15, SDG2), and (SDG14, SDG16) but with limitation with other goals drivers.

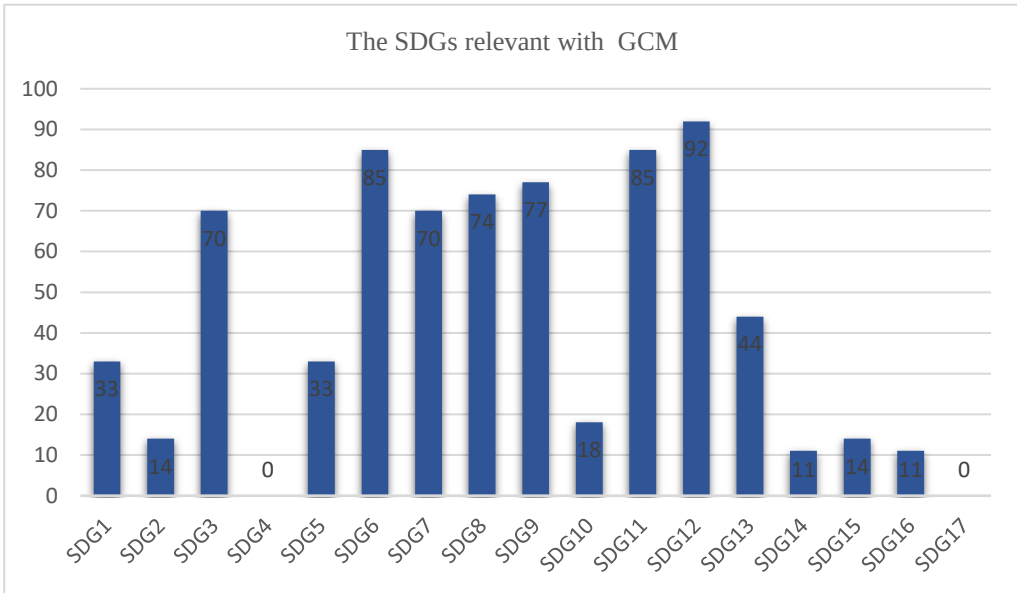


Figure 42. The most relevant SDGs for using GCM in residential buildings.

4.4.10. Green Concrete Materials Sustainability Framework (GCM- SF)

The framework is considered a tool for discussing the most important contributed SDGs and for utilizing GCM in Egyptian residential buildings' design and construction phases. It considers the inner links and network between the SDGs, and their targets for realizing SD 2030 agenda. For instance, SDG3 and its target 3.3 are aligned to enhance indoor air quality and improve human health by substituting CCM with GCM, which can reduce toxicity and pollution. In the same context, SDG12, in target 12.2, supports resource efficiency, reduces pollution, and decreases embodied carbon. Furthermore, target 12.5 is aligned with reducing waste, whereas the support for using sustainable construction materials is aligned with target 12.8. Figure 43. presents some of the most relevant SDGs and their targets, which strongly relate to realizing SDGs when using GCM in the Egyptian residential building sector. This will help apply a comprehensive and clear image for academic and industry realms. Furthermore, the framework increases scalability for more sustainable practices in future residential building projects. Therefore, GCM-SF is considered the first eco-friendly attempt. It can reduce and eliminate CCM's negative environmental impacts and improve its economic and social aspects.

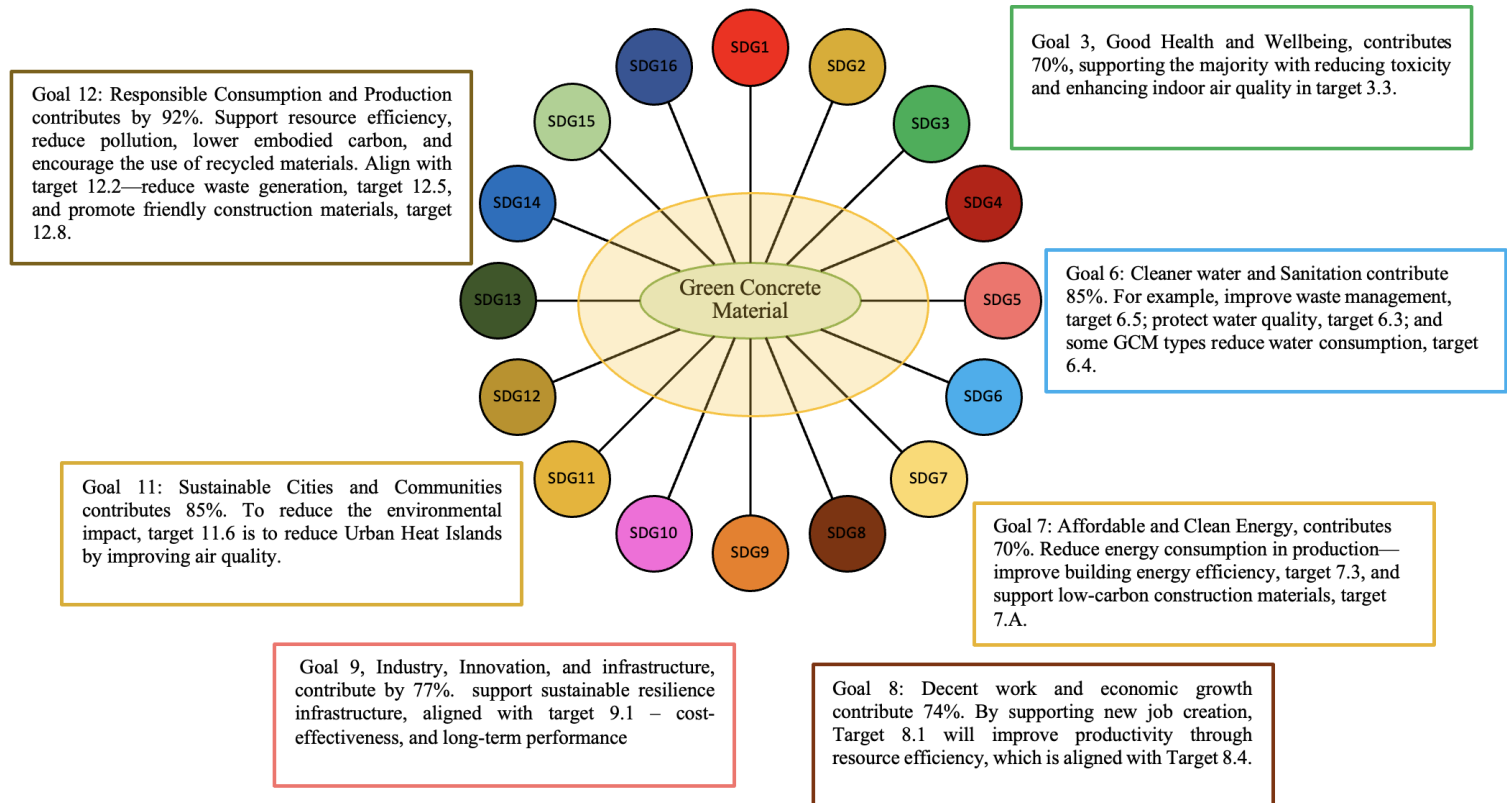


Figure 43. illustrates the most relevant SDGs and their target (source, author).

5. CONCLUSION

The current dissertation investigated the utilization of several GCMs scenarios, types, and strategies that are considered an environmentally friendly material in the design and construction phases of Egyptian residential building case studies. The eco-friendly approaches are used to introduce the use, selection, and evaluation of GCM to reduce negative environmental impacts such as CO₂ emissions, natural aggregate consumption, waste generation, and cost-effectiveness, which was consist of three stages as a following:

First, in the early design stage, the effects of using GCM were identified by the applied design-based solutions method for the building case study I, which was considered a novel tool to help reduce concrete and cement consumption, consequently protecting the environment and reducing negative environmental impacts, that can help achieve sustainability in the construction materials sector. The process started with redesigning the building to utilize the GCM, followed by the reselection, replacement, recycling, reuse, and reduction strategies. Furthermore, the substitution of CCM with GCM was analyzed and compared based on the original and modified scenarios using different concrete types for specific and selected building parts. Therefore, the replacement GCM is based on accurate and actual data for real and existing residential buildings located in New Borg Alarab City, Egypt. The selection of the building is due to its being considered a common building type in the study area's urban context. Thereby can successfully improve the sustainable features and promote the sustainable model to achieve a broad impact in the residential buildings sector. Consequently, the original design of the residential case study was modified to present a sustainable model that can replace CCM with GCM in non-structural works in specific building parts. This resulted in a significant reduction in cement that reached 19.5% in the modified B compared with the original A. Additionally, it resulted in a 44% reduction for the non-structural concrete for the selected part after applying RAC instead of OPC in non-structural works. In the same context, the study showed a significant reduction I sand, and NCA consumption after substituting CCM materials with GCM, which promotes a significant reduction in environmental burdens.

Second, in the construction process stage, the study investigated the role of GCM selection in reducing the environmental and economic impacts and emphasized the GCM's role in achieving a CE. Therefore, The SD-BF method was used to create the SDM for assessing the GCM circularity performance based

on real construction data collected from the second building case study located in New Cairo City, Egypt.

In this regard, the Vensim software was used to create the CLD and SF diagrams, revealing interrelationships in optimal GCM scenarios. The SD-BF method, aligned with CE principles, assesses the circularity performance of the most optimum scenarios. Identify and quantify the performance of different scenarios in terms of cement, NA, CO₂ emissions, waste, and cost-effectiveness during the construction phase. In this stage, the study explored the selection of GCM in residential building projects by partially substituting CCM with concrete types containing FA and RAC, considering the equivalent strength, durability, and functionality of CCM. We found that using an SDM can potentially affect GCM selection in actual and real-case studies of residential applications by providing time and cost benefits in the early stages of the construction process. Furthermore, SDM promotes the opportunity to identify the proper GCM type and scenario that contributes to the maximum benefits for reducing the CCM's negative impacts and applying CE.

Third, the dissertation identifies the GCM's role in attaining sustainable development by integrating the two global sustainability perspectives, SDGs and three sustainability pillars, to introduce the GCM types and strategies, especially suitable for residential building applications to identify and quantify the GCM-SI and their relation with SDGs in the sector. Therefore, the GCM-SF is being developed for sustainable development based on the two previous case study stages, supported by the comprehensive literature review of the previous research efforts. Thereby, the contributions of the GCM indicators were identified and classified based on an assessment-based approach to clarify the sustainability relationship. In this section, the study identified 27 GCM-SI contributed to the pillars and SDGs, which were classified to create the GCM-SF. In this regard, the high and low contribution levels were identified, which reflect the most important interactions, and found that the total number of goals had a significant contribution to GCM-S.

For example, there are 13 goals in the environment pillar, 12 goals within the social pillar, and 12 goals in the economic pillar; in the case of the goal, SDG17 is considered a constant goal. The results showed that in levels (very high and high), the most contribution goals are found in SDG12 and SDG11, and the minimum contribution in the levels (high and very high) found in both (SDG14 & SDG16), which are considered vital tools in achieving sustainability.

The dissertation proved that using GCM instead of CCM can reduce cement and natural aggregate consumption, waste generation, and CO₂ emissions, adding to the economic and social benefits. Therefore, the replacement of CCM should be considered during the design and construction stages. The simulation model promotes the first attempt for the construction and environmental stakeholders to identify the proper GCM types and scenarios that can contribute to CE maximum benefits and reduce the CCM's negative impacts on residential building projects. Finally, based on the results of this study, it is expected that GCM will yield sustainable construction activities in the residential building sector worldwide.

6. RECOMMENDATIONS

This dissertation recommended that formulating new rules and regulations and promoting cooperation between the decision-making and stakeholders regarding utilizing GCM in residential building projects have a tremendous role in achieving sustainability. An eco-friendly approach is a crucial solution and should be considered as a starting point for protecting the environment during the residential building's design and construction phases. Furthermore, it plays a crucial role for environmental scientists, architects, engineers, contractors, stakeholders, authorities, decision-makers, and cement and concrete industries.

While the dissertation's GCM-SF is limited to residential cases, it can be easily updated to use on various GCM for other building typologies at the construction and design phases and simulate the environmental performance to increase the benefits of reducing negative impacts and realizing sustainability for future construction projects. The dissertation emphasizes that more data and empirical studies are needed to promote further potential investigation, which will offer the possibility of integrating GCM knowledge required in new policy formulation and regulations for achieving CE. Meanwhile, selecting and using GCM to achieve sustainability requires more investigation for various project scales at local, regional, and global levels. Additionally, it emphasized that social indicators have a crucial role in increasing the utilization of GCM, and there is a need for more highlighting and investigation in future research.

6.1 The Study's Impact on Future Directions

Assessing the use and select GCM in the design and construction phases for the Egyptian residential building sector can provide future research by:

- Promote a conceptual framework to analyze the factors that influence the selection of GCM in residential buildings.
- Identify the utilization of GCM such as FA, RAC, and PCC, and compare various hypothetical GCM scenarios with the original scenario of (reinforced and non-reinforced) concrete for both (structural and non-structural) building parts enhanced the circularity performance and closing the CCM loop.
- Creating an SD-BF based on CE core principles helps identify the performance of GCM scenarios.

- Enhance the GCM selection by analyzing the simulation model through various scenarios.
- Using dynamic conditions to investigate the GCM variables provides valuable insights into the decision-making process.
- CLD clarifies the interrelationships of the GCM and the circularity variables.
- Develop the SF to help investigate the most optimum scenarios to quantify the reduction in cement, NA, CO₂ emissions, cost, and waste during the construction phase.
- SD model can provide various benefits for time and cost from the early stages of the construction process for GCM selection in real and existing residential building projects.
- GCM-SF presents an opportunity to facilitate the complexity of utilization of GCM in residential buildings and investigate strengths and weaknesses between the GCM-SI that contribute to the achievement of SDGs.

6.2 Suggestions for Future Research

The dissertation is a starting point for further research by expanding the sustainability assessment for various construction applications and building typologies. Furthermore, future research efforts should investigate different stages of using GCM, such as operation, maintenance, renovation, reconstruction, and disposal of landfills. In the same regard, the investigation for other GCMs should be extended, and their behavior with other sustainable building materials, considering other sustainability strategies and, moreover, addressing the challenge of long-term assessment for GCMs in the structural and non-structural building part under various climate conditions by using and integrating different types of GCM that can be applied to enhance workability and maintenance. Finally, this dissertation is considered a first attempt to examine the use and selection of GCM in the Egyptian residential buildings sector and is considered a call to action for different research directions in the future.

7. SUMMARY

Increasing the consumption of construction materials for residential buildings due to rapid population and urbanization growth has significant negative environmental impacts worldwide. In recent decades, the production of OPC has been associated with 8% of the world's human CO₂ emissions and significant negative environmental impacts due to its production process. It is considered the most common construction material used at the local and global levels and is considered one of the largest producers of CO₂ during its production process. However, the fast rate of population growth in Egypt has led to an increase in the number of residential buildings all over the country, resulting in a massive consumption of concrete and cement materials. Therefore, it is necessary to demonstrate alternative, innovative green solutions, such as GCM, to meet the needs of the country's urbanization without compromising natural resources for future development projects.

Therefore, the dissertation aims to assess the use and selection of GCM in the design and construction phases for residential buildings in Egypt in terms of reducing negative environmental impacts and consumption of natural resources. In this regard, the eco-friendly approach applied, consisting of three stages, as Design-based Solutions, system dynamic-based framework, and assessing-based approaches to investigate the benefits of using and selecting GCM applied in two residential buildings located in two new Egyptian cities, New Borg El-Arab City and New Cairo City in Egypt, as case studies. This selection of the building type was obtained due to it being considered a common building type in the study area's urban context.

In the case of study, I the dissertation aims to investigate the effects of substituting CCM with GCM in non-structural concrete works. It is considered the first attempt to answer what are the effects of using GCM on cement, natural aggregates, and CO₂ emissions. In this regard, we applied redesign, reduce, reselect, reuse, and recycle strategies to find an optimal solution for applying RAC as a replacement material in the selected building parts. By modifying the original design, we are obtained two building designs (the original and modified) with four different scenarios. Therefore, comparative analyses were applied to investigate the effects of different concrete materials to show the most optimum building cement and concrete reduction.

For example, 19.4% reduction in cement consumption in terms of the total concrete of the building and a 44.5% reduction in CO₂ emissions due to the

reduction of cement in specific building parts. In addition, this solution decreased NCA consumption by 23.7% in the final concrete.

In the second stage, the dissertation aims to identify and analyze the parameters affecting the selection of the GCM for case study II, based on the application of circularity performance and the achievement of CE principles by developing an SDM during the construction process. The system dynamic-based framework (SD-BF) is used to develop the CLD and SF diagrams to investigate the relation between the GCM variables during the thirty-month construction process for a residential building case study II located in New Cairo City, Egypt, by using Vensim software.

To investigate the simulation interaction of the variables between the GCM original and several hypothetical scenarios. Consequently, after running the simulation and analyzing the most appropriate scenarios that GCM, including fly FA and RAC in terms of cement, natural aggregate, CO₂ emissions, cost-effectiveness, and waste generation, the results showed that using various concrete scenarios could enhance the GCM selection, furthermore, the cement reduction is the most effective variable, and the reduction reached 19.8% and 11.4% in the most optimum scenarios, while the NA reduction reached 19.1% compared with the original scenario.

However, understanding the relationship between the GCM-SI and realizing SDGs remains an important task for using the GCM in the scope of the 2030 Agenda. Therefore, in the dissertation's third stage, the identification and assessment of the sustainability performance of GCM are introduced based on the two global sustainability perspectives, the SDGs and the three pillars as a governing context. Using an approach showed that GCM-SF has a significant role in clarifying the GCM and SDGs; for example, the level of the contribution showed that SDG 12 has a strong relation with 92%, as well as (SDG11 & SDG6) at 85%, while the (SDG14 &SDG16) have lower contributions by 11%, this for Egyptian residential building sector.

The current dissertation recommends that GCM close the loop of cementitious material consumption to reduce environmental impacts and achieve sustainability in the Egyptian building sector. Furthermore, SDM is considered a first attempt vital for achieving CE and closing the CCM loop, which helps construction decision-makers select suitable GCM for future residential projects. This can help in applying new rules and regulations for the use of GCMs in future residential projects. Further investigation is recommended to determine different building typologies and social sustainability aspects, considering the cooperation between private and public sectors in the Egyptian residential building industry.

7.1 New Scientific Achievements

Developing a sustainability assessment system for using GCM for residential buildings in the design and construction phases by providing a comprehensive approach consisting of three stages plays a crucial role in reducing the environmental burdens of the construction sector in Egypt. Integration between the sustainability perspectives promoted tremendous attention to the GCM's role as a starting point for enhancing the utilization of environmentally friendly materials and promoting sustainable practices in the future as a following:

- Develop a novel approach to design-based solutions or reducing environmental impacts by substituting CCM with GCM by applying re-design and modification in concrete materials for the structural and non-structural concrete in the specific building parts in the early design stage.
- Compare the original and modified building scenarios used to reduce cement consumption, which reached 19.5%, followed by estimating the CO₂ emissions based OPC production in all references and scenarios.
- Identify the most optimum scenario after quantifying the CCM and GCM in all scenarios' components by comparing cement, sand, natural coarse aggregate, and recycled coarse aggregate.
- Create the SDB-F as a novel tool for selecting GCM and identifying the circularity performance for achieving CE during the construction phase.
- Develop the CLD that is able to visualize the individual and causal links and feedback loops for several GCMs. That played a crucial role in demonstrating the selection of GCMs in the construction process as a complex system and applied the system structure based on the CE core principles for residential case study II.
- Create an SF diagram to enhance the GCM selection, which is considered a novel tool that can help in selecting between several GCM scenarios. Furthermore, the most optimum scenario can reduce the negative environmental impacts and enhance circularity performance during the construction process.
- Promote the GCM-SI based on previous results from the two case studies in the Egyptian residential sector and analyze the GCM behavior to realize SDGs.
- Develop a novel GCM-SF for residential buildings, which plays a crucial role and provides important insights to policymakers, environmental scientists, and stakeholders in the construction industry.

REFERENCES

- [1] Habitat U. Global housing demand at critical levels/ 2022. <https://unhabitat.org/topic/housing> (accessed July 3, 2023).
- [2] UN. Alliance, G. Global Status Report Executive Summary of the 2020 Global Status Report for Buildings and Construction 2020. United Nations: New York, NY, USA. 1–7.
- [3] Gao Y, Gao X, Zhang X. The 2 °C Global Temperature Target and the Evolution of the Long-Term Goal of Addressing Climate Change- From the United Nations Framework Convention on Climate Change to the Paris Agreement. *Engineering*, 2017;3:272–8
<https://doi.org/10.1016/J.ENG.2017.01.022>.
- [4] Alawneh R, Mohamed Ghazali FE, Ali H, Asif M. Assessing the contribution of water and energy efficiency in green buildings to achieve United Nations Sustainable Development Goals in Jordan. *Build Environ* 2018;146:119–32. <https://doi.org/10.1016/j.buildenv.2018.09.043>.
- [5] Scrucca F, Ingrao C, Barberio G, Matarazzo A, Lagioia G. On the role of sustainable buildings in achieving the 2030 UN sustainable development goals. *Environ Impact Assess Rev* 2023; 100:107069.
<https://doi.org/10.1016/j.eiar.2023.107069>.
- [6] Alawneh R, Ghazali F, Ali H, Sadullah AF. A Novel framework for integrating United Nations Sustainable Development Goals into sustainable non-residential building assessment and management in Jordan. *Sustain, Cities, Soc*, 2019;49:101612.
<https://doi.org/10.1016/j.scs.2019.101612>.
- [7] Long G, Gao Y, Xie Y. Designing more sustainable and greener self-compacting concrete. *Constr-Build-Mater*; 2015;84:301–6.
<https://doi.org/10.1016/j.conbuildmat.2015.02.072>.
- [8] Mehta PK. Greening of the Concrete Industry for Sustainable Development. *Concrete International* 2002;24:23–8.
- [9] Griffiths S, Sovacool BK, Furszyfer Del Rio DD, Foley AM, Bazilian MD, Kim J, et al. Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options. *Renewable and Sustainable Energy Reviews* 2023; 180:113291. <https://doi.org/10.1016/j.rser.2023.113291>.
- [10] Albidah A, Alghannam M, Abbas H, Almusallam T, Al-Salloum Y. Characteristics of metakaolin-based geopolymer concrete for different mix design parameters. *Journal of Materials Research and Technology* 2021;10:84–98. <https://doi.org/10.1016/j.jmrt.2020.11.104>.

- [11] Jindal BB, Alomayri T, Hasan A, Kaze CR. Geopolymer concrete with metakaolin for sustainability: a comprehensive review on raw material's properties, synthesis, performance, and potential application. *Environmental Science and Pollution Research* 2023;30:25299–324. <https://doi.org/10.1007/s11356-021-17849-w>.
- [12] Andrew RM. Global CO₂ emissions from cement production, 1928–2018. *Earth Syst Sci Data* 2019;11:1675–710. <https://doi.org/10.5194/essd-11-1675-2019>.
- [13] Müller HS, Haist M, Vogel M. Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime. *Constr Build Mater* 2014;67:321–37. <https://doi.org/10.1016/j.conbuildmat.2014.01.039>.
- [14] Le Quéré C, Andrew RM, Canadell JG, Sitch S, Ivar Korsbakken J, Peters GP, et al. *Global_Carbon_Budget_2013_v1.3.xlsx*. *Earth Syst Sci Data* 2017.
- [15] Habert G, Miller SA, John VM, Provis JL, Favier A, Horvath A, et al. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat Rev Earth Environ* 2020;1:559–73. <https://doi.org/10.1038/s43017-020-0093-3>.
- [16] Garside M. G cement production 1995–2019. No Title Global cement production 1995–2019. Statista, Dostupno Na: <https://www-statista-com/statistics/267364/World-Cement-Production-Bycountry/> (Pristupljeno: 17 Siječnja 2020) n.d.
- [17] Chen H, Chow CL, Lau D. Developing green and sustainable concrete in integrating with different urban wastes. *J Clean Prod* 2022;368:133057. <https://doi.org/10.1016/j.jclepro.2022.133057>.
- [18] Sivakrishna A, Adesina A, Awoyera PO, Kumar KR. Green concrete: A review of recent developments. *Mater Today Proc* 2020;27:54–8. <https://doi.org/10.1016/j.matpr.2019.08.202>.
- [19] Suhendro B. Toward green concrete for better sustainable environment. *Procedia Eng* 2014;95:305–20. <https://doi.org/10.1016/j.proeng.2014.12.190>.
- [20] Dhanya BS, Santhanam M, Gettu R, Pillai RG. Performance evaluation of concretes having different supplementary cementitious material dosages belonging to different strength ranges. *Constr Build Mater* 2018;187:984–95. <https://doi.org/10.1016/j.conbuildmat.2018.07.185>.
- [21] Hafez H, Kurda R, Cheung WM, Nagaratnam B. A systematic review of the discrepancies in life cycle assessments of green concrete. *Applied Sciences (Switzerland)* 2019;9. <https://doi.org/10.3390/app9224803>.

- [22] Amran YHM, Alyousef R, Alabduljabbar H, El-Zeadani M. Clean production and properties of geopolymer concrete; A review. *J Clean Prod* 2020;251:119679. <https://doi.org/10.1016/j.jclepro.2019.119679>.
- [23] Meyer C. The greening of the concrete industry. *Cem Concr Compos* 2009;31:601–5. <https://doi.org/10.1016/j.cemconcomp.2008.12.010>.
- [24] Marey H, Kozma G, Szabó G. Effects of Using Green Concrete Materials on the CO2 Emissions of the Residential Building Sector in Egypt. *Sustainability (Switzerland)* 2022;14. <https://doi.org/10.3390/su14063592>.
- [25] Yu W Der, Cheng ST, Ho WC, Chang YH. Measuring the sustainability of construction projects throughout their lifecycle: A Taiwan Lesson. *Sustainability (Switzerland)* 2018;10. <https://doi.org/10.3390/su10051523>.
- [26] Zhao Y, Yu M, Xiang Y, Kong F, Li L. A sustainability comparison between green concretes and traditional concrete using an emergy ternary diagram. *J Clean Prod* 2020;256:120421. <https://doi.org/10.1016/j.jclepro.2020.120421>.
- [27] Opoku A, Deng J, Elmualim A, Ekung S, Hussein AA, Buhashima Abdalla S. Sustainable procurement in construction and the realisation of the sustainable development goal (SDG) 12. *J Clean Prod* 2022;376:134294. <https://doi.org/10.1016/j.jclepro.2022.134294>.
- [28] WBCSD and ARUP. Net-zero buildings: Where do we stand ? *Wbcsd* 2021:103.
- [29] Ruparathna R, Hewage K. Sustainable procurement in the Canadian construction industry: Current practices, drivers and opportunities. *J Clean Prod* 2015;109:305–14. <https://doi.org/10.1016/j.jclepro.2015.07.007>.
- [30] Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. Barriers to achieving sustainable construction project procurement in the private sector. *J Cleaner engineering and technology* 2021; <https://doi.org/10.1016/j.clet.2021.100125>
- [31] Nilimaa J. Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment* 2023;15:100177. <https://doi.org/10.1016/j.dibe.2023.100177>.
- [32] Baynes TM, Musango JK. Estimating current and future global urban domestic material consumption. *Environmental Research Letters* 2018;13. <https://doi.org/10.1088/1748-9326/aac391>.
- [33] Frischknecht R, Birgisdottir H, Chae CU, Lützkendorf T, Passer A. IEA EBC Annex 72 - Assessing life cycle related environmental impacts

- caused by buildings - Targets and tasks. IOP Conf Ser Earth Environ Sci 2019;323. <https://doi.org/10.1088/1755-1315/323/1/012042>.
- [34] Bobba S, Carrara S, Huisman J, Mathieux F, Pavel C. Critical Raw Materials for Strategic Technologies and Sectors in the EU - a Foresight Study. 2020. <https://doi.org/10.2873/58081>.
- [35] Miller SA, Horvath A, Monteiro PJM. Impacts of booming concrete production on water resources worldwide. *Nat Sustain* 2018;1:69–76. <https://doi.org/10.1038/s41893-017-0009-5>.
- [36] Global Alliance for Buildings and Construction, International Energy Agency the UNEP. GlobalABC roadmap for buildings and construction: towards a zero-emission, efficient and resilient buildings, and construction sector. Paris: n.d.
- [37] International Energy Agency. 2019 Global Status report for Buildings and Construction. 2019.
- [38] Gamaleldine M, Corvacho H. Compliance with Building Energy Code for the Residential Sector in Egyptian Hot-Arid Climate: Potential Impact, Difficulties, and Further Improvements. *Sustainability (Switzerland)* 2022;14. <https://doi.org/10.3390/su14073936>.
- [39] Romo-Orozco JM, Contreras-Jiménez JC, Corona-Armenta JR, Morales-Mendoza LF. A methodological approach to evaluate structural building projects through the Environmental Economic Index. *Clean Technol Environ Policy* 2022;24:901–18. <https://doi.org/10.1007/s10098-021-02230-9>.
- [40] Hu S, Zhang Y, Yang Z, Yan D, Jiang Y. Challenges and opportunities for carbon neutrality in China’s building sector—Modelling and data. *Build Simul* 2022;15:1899–921. <https://doi.org/10.1007/s12273-022-0912-1>.
- [41] Torres A, Simoni MU, Keiding JK, Müller DB, zu Ermgassen SOSE, Liu J, et al. Sustainability of the global sand system in the Anthropocene. *One Earth* 2021;4:639–50. <https://doi.org/10.1016/j.oneear.2021.04.011>.
- [42] de Leeuw J, Shankman D, Wu G, de Boer WF, Burnham J, He Q, et al. Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China. *Reg Environ Change* 2010;10:95–102. <https://doi.org/10.1007/s10113-009-0096-6>.
- [43] Sreebha S, Padmalal D. Environmental impact assessment of sand mining from the small catchment rivers in the Southwestern Coast of India: A case study. *Environ Manage* 2011;47:130–40. <https://doi.org/10.1007/s00267-010-9571-6>.

- [44] Emad R, El-Hady A, Farouk A, Mohamed A. Thermal Performance Evaluation of Bio-Bricks and Conventional Bricks in Residential Buildings in Aswan City, Egypt. *Sci Rep* 2023;1–14. <https://doi.org/10.1038/s41598-023-42228-5>.
- [45] Fahmy M, Mahdy MM, Nikolopoulou M. Prediction of future energy consumption reduction using GRC envelope optimization for residential buildings in Egypt. *Energy Build* 2014;70:186–93. <https://doi.org/10.1016/j.enbuild.2013.11.057>.
- [46] Daoud AO, Othman AAE, Ebohon OJ, Bayyati A. Analysis of factors affecting construction and demolition waste reduction in Egypt. *International Journal of Construction Management* 2023;23:1395–404. <https://doi.org/10.1080/15623599.2021.1974682>.
- [47] Annual Bulletin of Construction and. Central Agency of Public Mobilization & Statistics. https://www.capmas.gov.eg/Pages/Publications.aspx?page_id=5104&YearID=23317 (accessed September 20, 2023).
- [48] Abdelrahman Hussein AA, Pollock E. Sustainable Development approaches in Egypt. *IOP Conf Ser Earth Environ Sci* 2019;297. <https://doi.org/10.1088/1755-1315/297/1/012027>.
- [49] Komkova A, Habert G. Optimal supply chain networks for waste materials used in alkali-activated concrete fostering circular economy. *Resour Conserv Recycl* 2023;193:106949. <https://doi.org/10.1016/J.RESCONREC.2023.106949>.
- [50] Favier A, De Wolf C, Scrivener K, Habert G. A sustainable future for the European Cement and Concrete Industry Technology assessment for full decarbonisation of the industry by 2050. *BRISK Binary Robust Invariant Scalable Keypoints* 2018:12–9.
- [51] Penrose B, Penrose B. Occupational Exposure to Cement Dust : Changing Opinions of a Respiratory Hazard Published by : Australian and New Zealand Society of the History of Medicine , Inc Linked references are available on JSTOR for this article : Occupational Exposure to Cement 2014;16:25–44.
- [52] Bajželj B, Allwood JM, Cullen JM. Designing climate change mitigation plans that add up. *Environ Sci Technol* 2013;47:8062–9. <https://doi.org/10.1021/es400399h>.
- [53] Miller SA, John VM, Pacca SA, Horvath A. Carbon dioxide reduction potential in the global cement industry by 2050. *Cem Concr Res* 2018;114:115–24. <https://doi.org/10.1016/J.CEMCONRES.2017.08.026>.

- [54] Nehdi, M. L., Marani, A., & Zhang, L. (Is net-zero feasible: Systematic review of cement and concrete decarbonization technologies. *Renewable and Sustainable Energy Reviews* 2024;191:114169.
<https://doi.org/10.1016/j.rser.2023.114169>
- [55] Huntzinger DN, Eatmon TD. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *J Clean Prod* 2009;17:668–75.
<https://doi.org/10.1016/j.jclepro.2008.04.007>.
- [56] Watari, T., Cao, Z., Hata, S., & Nansai, K. Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions. *Nature communications* 2022; 13(1), 4158.
<https://doi.org/10.1038/s41467-022-31806-2>
- [57] Habert G, Bouzidi Y, Chen C, Jullien A. Development of a depletion indicator for natural resources used in concrete. *Resour Conserv Recycl* 2010;54:364–76. <https://doi.org/10.1016/j.resconrec.2009.09.002>.
- [58] Busch, P., Kendall, A., Murphy, C. W., & Miller, S. A. Literature review on policies to mitigate GHG emissions for cement and concrete. *Resources, Conservation and Recycling* 2022; 182, 106278.
<https://doi.org/10.1016/j.resconrec.2022.106278>
- [59] Salas, D. A., Ramirez, A. D., Rodríguez, C. R., Petroche, D. M., Boero, A. J., & Duque-Rivera, J. Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review. *Journal of Cleaner Production*; 2016; 113, 114-122.
<https://doi.org/10.1016/j.jclepro.2015.11.078>
- [60] Schneider M, Hoenig V, Ruppert J, Rickert J. The cement plant of tomorrow. *Cem Concr Res* 2023;173.
<https://doi.org/10.1016/j.cemconres.2023.107290>.
- [61] Schneider M, Romer M, Tschudin M, Bolio H. Sustainable cement production-present and future. *Cem Concr Res* 2011;41:642–50.
<https://doi.org/10.1016/j.cemconres.2011.03.019>.
- [62] Le Quéré C, Andrew RM, Canadell JG, Sitch S, Ivar Korsbakken J, Peters GP, et al. *Global_Carbon_Budget_2013_v1.3.xlsx*. Earth Syst Sci Data 2017.
- [63] Bildirici ME. Cement production, environmental pollution, and economic growth: evidence from China and USA. *Clean Technol Environ Policy* 2019;21:783–93. <https://doi.org/10.1007/s10098-019-01667-3>.
- [64] Arrigoni A, Panesar DK, Duhamel M, Opher T, Saxe S, Posen ID, et al. Life cycle greenhouse gas emissions of concrete containing

- supplementary cementitious materials: cut-off vs. substitution. *J Clean Prod* 2020;263:121465. <https://doi.org/10.1016/j.jclepro.2020.121465>.
- [65] Serikawa M, Satoh M, Umishio W, Kawakubo S, Nakano J, Akimoto T, et al. Quantitative Evaluation of the Contributions of Improved Housing Performances Toward Delivering Sustainable Development Goals by a Building Energy Simulation Tool. *Sustain Cities Soc* 2022;79:103701. <https://doi.org/10.1016/j.scs.2022.103701>.
- [66] Olubunmi OA, Xia PB, Skitmore M. Green building incentives: A review. *Renewable and Sustainable Energy Reviews* 2016;59:1611–21. <https://doi.org/10.1016/j.rser.2016.01.028>.
- [67] Assi LN, Carter K, Deaver E, Ziehl P. Review of availability of source materials for geopolymer/sustainable concrete. *J Clean Prod* 2020;263:121477. <https://doi.org/10.1016/j.jclepro.2020.121477>.
- [68] Barcelo L, Kline J, Walenta G, Gartner E. Cement and carbon emissions. *Materials and Structures/Materiaux et Constructions* 2014;47:1055–65. <https://doi.org/10.1617/s11527-013-0114-5>.
- [69] Yang KH, Jung YB, Cho MS, Tae SH. Effect of supplementary cementitious materials on reduction of CO₂ emissions from concrete. *J Clean Prod* 2015;103:774–83. <https://doi.org/10.1016/j.jclepro.2014.03.018>.
- [70] Ding GKC. Sustainable construction-The role of environmental assessment tools. *J Environ Manage* 2008;86:451–64. <https://doi.org/10.1016/j.jenvman.2006.12.025>.
- [71] Müller, H. S., Breiner, R., Moffatt, J. S., & Haist, M. Design and properties of sustainable concrete. *Procedia Engineering*; 2014; 95, 290-304. <https://doi.org/10.1016/j.proeng.2014.12.189>
- [72] Sánchez-Garrido AJ, Navarro IJ, Yepes V. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *J Clean Prod* 2022;330. <https://doi.org/10.1016/j.jclepro.2021.129724>.
- [73] Invidiata A, Lavagna M, Ghisi E. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. *Build Environ* 2018;139:58–68. <https://doi.org/10.1016/j.buildenv.2018.04.041>.
- [74] Miranda de Souza A, Soares de Lima GE, Nalon GH, Salgado Lopes MM, Luís de Oliveira Júnior A, Rodrigues Lopes GJ, et al. Application of the desirability function for the development of new composite eco-efficiency indicators for concrete. *Journal of Building Engineering* 2021;40. <https://doi.org/10.1016/j.job.2021.102374>.

- [75] Goubran S. On the Role of Construction in Achieving the SDGs. *Journal of Sustainability Research* 2019;1:1–52.
<https://doi.org/10.20900/jsr20190020>.
- [76] Vishwakarma, V., & Uthaman, S. Environmental impact of sustainable green concrete. In *Smart Nanoconcretes and Cement-Based Materials*; 2020; (pp. 241-255). Elsevier. <https://doi.org/10.1016/B978-0-12-817854-6.00009-X>
- [77] Esmaeili, J., & AL-Mwanes, A. O. A review: Properties of eco-friendly ultra-high-performance concrete incorporated with waste glass as a partial replacement for cement. *Materials Today: Proceedings*, (2021). 42, 1958-1965. <https://doi.org/10.1016/j.matpr.2020.12.242>
- [78] Chen W, Jin R, Xu Y, Wanatowski D, Li B, Yan L, et al. Adopting recycled aggregates as sustainable construction materials: A review of the scientific literature. *Constr Build Mater* 2019;218:483–96.
<https://doi.org/10.1016/j.conbuildmat.2019.05.130>.
- [79] Imbabi MS, Carrigan C, McKenna S. Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment* 2012;1:194–216.
<https://doi.org/10.1016/j.ijbsbe.2013.05.001>.
- [80] Awoyera PO, Akinmusuru JO, Ndambuki JM. Green concrete production with ceramic wastes and laterite. *Constr Build Mater* 2016;117:29–36. <https://doi.org/10.1016/j.conbuildmat.2016.04.108>.
- [81] Xuan D, Poon CS, Zheng W. Management and sustainable utilization of processing wastes from ready-mixed concrete plants in construction: A review. *Resour Conserv Recycl* 2018;136:238–47.
<https://doi.org/10.1016/j.resconrec.2018.04.007>.
- [82] Arioğlu Akan MÖ, Dhavale DG, Sarkis J. Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain. *J Clean Prod* 2017;167:1195–207.
<https://doi.org/10.1016/j.jclepro.2017.07.225>.
- [83] Aprianti S E. A huge number of artificial waste material can be supplementary cementitious material (SCM) for concrete production – a review part II. *J Clean Prod* 2017;142:4178–94.
<https://doi.org/10.1016/j.jclepro.2015.12.115>.
- [84] Cuenca-Moyano GM, Cabrera M, López-Alonso M, Martínez-Echevarría MJ, Agrela F, Rosales J. Design of lightweight concrete with olive biomass bottom ash for use in buildings. *Journal of Building Engineering* 2023;69:106289. <https://doi.org/10.1016/j.jobbe.2023.106289>.

- [85] Yehia S, Helal K, Abusharkh A, Zaher A, Istaitiyeh H. Strength and Durability Evaluation of Recycled Aggregate Concrete. *Int J Concr Struct Mater* 2015;9:219–39. <https://doi.org/10.1007/s40069-015-0100-0>.
- [86] Golewski GL. Green concrete composite incorporating fly ash with high strength and fracture toughness. *J Clean Prod* 2018;172:218–26. <https://doi.org/10.1016/j.jclepro.2017.10.065>.
- [87] Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr Build Mater* 2009;23:28–39. <https://doi.org/10.1016/j.conbuildmat.2007.11.012>.
- [88] Hemalatha T, Ramaswamy A. A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. *J Clean Prod* 2017;147:546–59. <https://doi.org/10.1016/j.jclepro.2017.01.114>.
- [89] Lothenbach B, Scrivener K, Hooton RD. Supplementary cementitious materials. *Cem Concr Res* 2011;41:1244–56. <https://doi.org/10.1016/J.CEMCONRES.2010.12.001>.
- [90] Paris JM, Roessler JG, Ferraro CC, Deford HD, Townsend TG. A review of waste products utilized as supplements to Portland cement in concrete. *J Clean Prod* 2016;121:1–18. <https://doi.org/10.1016/j.jclepro.2016.02.013>.
- [91] Błaszczyński T, Król M. Usage of Green Concrete Technology in Civil Engineering. *Procedia Eng* 2015;122:296–301. <https://doi.org/10.1016/j.proeng.2015.10.039>.
- [92] Ozbakkaloglu T, Gholampour A, Xie T. Mechanical and Durability Properties of Recycled Aggregate Concrete: Effect of Recycled Aggregate Properties and Content. *Journal of Materials in Civil Engineering* 2018;30. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0002142](https://doi.org/10.1061/(asce)mt.1943-5533.0002142).
- [93] Ebohon O, Momoh J. Existing sustainability rating systems in adopting waste reuse. 2023. <https://doi.org/10.1016/B978-0-323-89838-6.00009-8>.
- [94] Gettu R, Pillai RG, Santhanam M, Basavaraj AS, Rathnarajan S, Dhanya BS. Sustainability-based decision support framework for choosing concrete mixture proportions. *Materials and Structures/Materiaux et Constructions* 2018; 51:1–16. <https://doi.org/10.1617/s11527-018-1291z>.
- [95] Al-Gahtani K, Alsulaihi I, Ali M, Marzouk M. Production of green concrete using recycled waste aggregate and byproducts. *Built Environment Project and Asset Management* 2017; 7:413–25. <https://doi.org/10.1108/BEPAM-09-2016-0047>.

- [96] Mi R, Pan G, Liew KM, Kuang T. Utilizing recycled aggregate concrete in sustainable construction for a required compressive strength ratio. *J Clean Prod* 2020;276:124249.
<https://doi.org/10.1016/j.jclepro.2020.124249>.
- [97] Zhang LW, Sojobi AO, Kodur VKR, Liew KM. Effective utilization and recycling of mixed recycled aggregates for a greener environment. *J Clean Prod* 2019;236:117600.
<https://doi.org/10.1016/j.jclepro.2019.07.075>.
- [98] Duan Z, Singh A, Xiao J, Hou S. Combined use of recycled powder and recycled coarse aggregate derived from construction and demolition waste in self-compacting concrete. *Constr Build Mater* 2020; 254:119323. <https://doi.org/10.1016/j.conbuildmat.2020.119323>.
- [99] Marvila M, de Matos P, Rodríguez E, Monteiro SN, de Azevedo ARG. Recycled Aggregate: A Viable Solution for Sustainable Concrete Production. *Materials* 2022; 15:1–16.
<https://doi.org/10.3390/ma15155276>.
- [100] Azevedo ARG, Cecchin D, Carmo DF, Silva FC, Campos CMO, Shtrucka TG, et al. Analysis of the compactness and properties of the hardened state of mortars with recycling of construction and demolition waste (CDW). *Journal of Materials Research and Technology* 2020; 9:5942–52. <https://doi.org/10.1016/j.jmrt.2020.03.122>.
- [101] Robalo K, Costa H, do Carmo R, Júlio E. Experimental development of low cement content and recycled construction and demolition waste aggregates concrete. *Constr Build Mater* 2021; 273:121680.
<https://doi.org/10.1016/j.conbuildmat.2020.121680>.
- [102] Tam VWY, Soomro M, Evangelista ACJ. A review of recycled aggregate in concrete applications (2000–2017). *Constr Build Mater* 2018; 172:272–92. <https://doi.org/10.1016/j.conbuildmat.2018.03.240>.
- [103] Al-Mansour A, Chow CL, Feo L, Penna R, Lau D. Green concrete: By-product's utilization and advanced approaches. *Sustainability* (Switzerland) 2019; 11:1–30. <https://doi.org/10.3390/su11195145>.
- [104] Cantero B, Bravo M, de Brito J, Sáez Del Bosque IF, Medina C. Assessment of the permeability to aggressive agents of concrete with recycled cement and mixed recycled aggregate. *Applied Sciences* (Switzerland) 2021;11. <https://doi.org/10.3390/app11093856>.
- [105] Joseph HS, Pachiappan T, Avudaiappan S, Flores EIS. A Study on Mechanical and Microstructural Characteristics of Concrete Using Recycled Aggregate. *Materials* 2022;15.
<https://doi.org/10.3390/ma15217535>.

- [106] Pacheco J, de Brito J. Recycled aggregates produced from construction and demolition waste for structural concrete: Constituents, properties and production. *Materials* 2021;14. <https://doi.org/10.3390/ma14195748>.
- [107] Colangelo F, Forcina A, Farina I, Petrillo A. Life Cycle Assessment (LCA) of different kinds of concrete containing waste for sustainable construction. *Buildings* 2018;8. <https://doi.org/10.3390/buildings8050070>.
- [108] El-Hawary MT, Koenke C, El-Nemr A, Hanna NF. Using Recycled Concrete as a Replacement for Coarse Aggregate in the Production of Green Concrete. In: Shehata H, El-Badawy S, editors. *Sustainable Issues in Infrastructure Engineering*, Cham: Springer International Publishing; 2021, p. 127–51.
- [109] Shmlls M, Abed M, Fořt J, Horvath T, Bozsaky D. Towards closed-loop concrete recycling: Life cycle assessment and multi-criteria analysis. *J Clean Prod* 2023;410. <https://doi.org/10.1016/j.jclepro.2023.137179>.
- [110] Halahla AM, Akhtar M, Almasri AH. Utilization of Demolished Waste as Coarse Aggregate in Concrete. *Civil Engineering Journal* 2019;5:540. <https://doi.org/10.28991/cej-2019-03091266>.
- [111] de Juan MS, Gutiérrez PA. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Constr Build Mater* 2009; 23:872–7. <https://doi.org/10.1016/j.conbuildmat.2008.04.012>.
- [112] Berndt ML. Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Constr Build Mater* 2009; 23:2606–13. <https://doi.org/10.1016/j.conbuildmat.2009.02.011>.
- [113] Rahal K. Mechanical properties of concrete with recycled coarse aggregate. *Build Environ* 2007; 42:407–15. <https://doi.org/10.1016/j.buildenv.2005.07.033>.
- [114] Samad S, Shah A. Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review. *International Journal of Sustainable Built Environment* 2017; 6:663–74. <https://doi.org/10.1016/j.ijsbe.2017.07.003>.
- [115] Tang Q, Ma Z, Wu H, Wang W. The utilization of eco-friendly recycled powder from concrete and brick waste in new concrete: A critical review. *Cem Concr Compos* 2020;114:103807. <https://doi.org/10.1016/j.cemconcomp.2020.103807>.
- [116] Habibi A, Ramezaniapour AM, Mahdikhani M, Bamshad O. RSM-based evaluation of mechanical and durability properties of recycled

aggregate concrete containing GGBFS and silica fume. *Constr Build Mater* 2021;270:121431.

<https://doi.org/10.1016/j.conbuildmat.2020.121431>.

- [117] Benjamin A. G. Material Property Characterization of Ultra-High Performance Concrete. *Fhwa* 2006:186.
- [118] Thomas M. Optimizing the Use of Fly Ash in Concrete. *Portland Cement Association* 2007.
- [119] Nath P, Sarker P. Effect of fly ash on the durability properties of high strength concrete. *Procedia Eng* 2011;14:1149–56.
<https://doi.org/10.1016/j.proeng.2011.07.144>.
- [120] Oleksik M, Dobrotă D, Sabin Dimulescu C, Dumitrașcu O, Petrașcu R. Advanced use of waste rubber and fly ash to ensure an efficient circular economy. *Ain Shams Engineering Journal* 2023.
<https://doi.org/10.1016/j.asej.2023.102264>.
- [121] Deng Y, Yan C, Zhang J, Yin L, Liu S, Yan Y. Preparation and mechanical characterization of engineered cementitious composites with high-volume fly ash and waste glass powder. *J Clean Prod* 2022;333:130222. <https://doi.org/10.1016/j.jclepro.2021.130222>.
- [122] Velenturf APM, Purnell P. Principles for a sustainable circular economy. *Sustain Prod Consum* 2021;27:1437–57.
<https://doi.org/10.1016/j.spc.2021.02.018>.
- [123] Teixeira ER, Mateus R, Camões AF, Bragança L, Branco FG. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *J Clean Prod* 2016;112:2221–30.
<https://doi.org/10.1016/j.jclepro.2015.09.124>.
- [124] Saldarriaga JF, Gaviria X, Gene JM, Aguado R. Improving circular economy by assessing the use of fly ash as a replacement of lime pastes reducing its environmental impact. *Process Safety and Environmental Protection* 2022;159:1008–18.
<https://doi.org/10.1016/j.psep.2022.01.074>.
- [125] Huang CH, Lin SK, Chang CS, Chen HJ. Mix proportions and mechanical properties of concrete containing very high-volume of Class F fly ash. *Constr Build Mater* 2013;46:71–8.
<https://doi.org/10.1016/j.conbuildmat.2013.04.016>.
- [126] Ahmad W, Ahmad A, Ostrowski KA, Aslam F, Joyklad P. A scientometric review of waste material utilization in concrete for sustainable construction. *Case Studies in Construction Materials* 2021;15:e00683. <https://doi.org/10.1016/j.cscm.2021.e00683>.

- [127] Schöggel JP, Stumpf L, Baumgartner RJ. The narrative of sustainability and circular economy - A longitudinal review of two decades of research. *Resour Conserv Recycl* 2020;163:105073. <https://doi.org/10.1016/j.resconrec.2020.105073>.
- [128] Geisendorf S, Pietrulla F. The circular economy and circular economic concepts—a literature analysis and redefinition. *Thunderbird International Business Review* 2018;60:771–82. <https://doi.org/10.1002/tie.21924>.
- [129] Blomsma F, Brennan G. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *J Ind Ecol* 2017;21:603–14. <https://doi.org/10.1111/jiec.12603>.
- [130] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour Conserv Recycl* 2017;127:221–32. <https://doi.org/10.1016/j.resconrec.2017.09.005>.
- [131] Gartner E, Hirao H. A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete. *Cem Concr Res* 2015;78:126–42. <https://doi.org/10.1016/j.cemconres.2015.04.012>.
- [132] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cem Concr Res* 2018;114:2–26. <https://doi.org/10.1016/j.cemconres.2018.03.015>.
- [133] Merli R, Preziosi M, Acampora A. How do scholars approach the circular economy? A systematic literature review. *J Clean Prod* 2018;178:703–22. <https://doi.org/10.1016/j.jclepro.2017.12.112>.
- [134] Nodehi M, Taghvaei VM. Applying Circular Economy to Construction Industry through Use of Waste Materials: A Review of Supplementary Cementitious Materials, Plastics, and Ceramics. vol. 2. Springer International Publishing; 2022. <https://doi.org/10.1007/s43615-022-00149-x>.
- [135] Marsh ATM, Velenturf APM, Bernal SA. Circular Economy strategies for concrete: implementation and integration. *J Clean Prod* 2022;362:132486. <https://doi.org/10.1016/j.jclepro.2022.132486>.
- [136] Marey H, Kozma G, Szabó G. Green concrete materials selection for achieving circular economy in residential buildings using system dynamics. *Cleaner Materials* 2024;11. <https://doi.org/10.1016/j.clema.2024.100221>.
- [137] Kalmykova Y, Sadagopan M, Rosado L. Circular economy - From review of theories and practices to development of implementation tools.

Resour Conserv Recycl 2018;135:190–201.

<https://doi.org/10.1016/j.resconrec.2017.10.034>.

- [138] Murray A, Skene K, Haynes K. The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics* 2017;140:369–80.
<https://doi.org/10.1007/s10551-015-2693-2>.
- [139] Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J Clean Prod* 2016;114:11–32.
<https://doi.org/10.1016/j.jclepro.2015.09.007>.
- [140] Urbinati A, Chiaroni D, Chiesa V. Towards a new taxonomy of circular economy business models. *J Clean Prod* 2017;168:487–98.
<https://doi.org/10.1016/j.jclepro.2017.09.047>.
- [141] Suchek N, Fernandes CI, Kraus S, Filser M, Sjögrén H. Innovation and the circular economy: A systematic literature review. *Bus Strategy Environ* 2021;30:3686–702. <https://doi.org/10.1002/bse.2834>.
- [142] Liew KM, Sojobi AO, Zhang LW. Green concrete: Prospects and challenges. *Constr Build Mater* 2017;156:1063–95.
<https://doi.org/10.1016/j.conbuildmat.2017.09.008>.
- [143] Veite CJ, Steinhilper R. Complexity in a circular economy: A need for rethinking complexity management strategies. *Lecture Notes in Engineering and Computer Science* 2016;2224:763–8.
- [144] Lederer J, Gassner A, Kleemann F, Fellner J. Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna. *Resour Conserv Recycl* 2020;161:104942. <https://doi.org/10.1016/j.resconrec.2020.104942>.
- [145] Spišáková M, Mandíček T, Mésároš P, Špak M. Waste Management in a Sustainable Circular Economy as a Part of Design of Construction. *Applied Sciences (Switzerland)* 2022;12.
<https://doi.org/10.3390/app12094553>.
- [146] Nodehi M, Mohamad Taghvaei V. Sustainable concrete for circular economy: a review on use of waste glass. *Glass Structures and Engineering* 2022;7:3–22. <https://doi.org/10.1007/s40940-021-00155-9>.
- [147] Tazi N, Idir R, Ben Fraj A. Towards achieving circularity in residential building materials: Potential stock, locks and opportunities. *J Clean Prod* 2021;281:124489. <https://doi.org/10.1016/j.jclepro.2020.124489>.
- [148] Jokar Z, Mokhtar A. Policy making in the cement industry for CO₂ mitigation on the pathway of sustainable development- A system

- dynamics approach. *J Clean Prod* 2018;201:142–55.
<https://doi.org/10.1016/j.jclepro.2018.07.286>.
- [149] Sterman_. *New Business Models for the Knowledge Economy*. vol. 26. 2010. <https://doi.org/10.1108/sd.2010.05626aae.001>.
- [150] Feng YY, Chen SQ, Zhang LX. System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecol Modell* 2013;252:44–52.
<https://doi.org/10.1016/J.ECOLMODEL.2012.09.008>.
- [151] Fong WK, Matsumoto H, Lun YF, Kimura R. System dynamic model for the prediction of urban energy consumption trends. *IAQVEC 2007 Proceedings - 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings: Sustainable Built Environment 2007*;1:757–64.
- [152] Sheheryar M, Rehan R, Nehdi ML. Estimating co2 emission savings from ultrahigh performance concrete: A system dynamics approach. *Materials* 2021;14:1–22. <https://doi.org/10.3390/ma14040995>.
- [153] Lauf S, Haase D, Hostert P, Lakes T, Kleinschmit B. Uncovering land-use dynamics driven by human decision-making - A combined model approach using cellular automata and system dynamics. *Environmental Modelling and Software* 2012;27–28:71–82.
<https://doi.org/10.1016/j.envsoft.2011.09.005>.
- [154] Nehdi M, Rehan R, Simonovic SP. System dynamics model for sustainable cement and concrete: Novel tool for policy analysis. *ACI Mater J* 2004;101:216–25. <https://doi.org/10.14359/13117>.
- [155] Anand S, Vrat P, Dahiya RP. Application of a system dynamics approach for assessment and mitigation of CO2 emissions from the cement industry. *J Environ Manage* 2006;79:383–98.
<https://doi.org/10.1016/j.jenvman.2005.08.007>.
- [156] Ansari N, Seifi A. A system dynamics model for analyzing energy consumption and CO2 emission in Iranian cement industry under various production and export scenarios. *Energy Policy* 2013;58:75–89.
<https://doi.org/10.1016/j.enpol.2013.02.042>.
- [157] Proaño L, Sarmiento AT, Figueredo M, Cobo M. Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: A system dynamics approach. *J Clean Prod* 2020;263.
<https://doi.org/10.1016/j.jclepro.2020.121457>.
- [158] Ekinci E, Kazancoglu Y, Mangla SK. Using system dynamics to assess the environmental management of cement industry in streaming data

- context. *Science of the Total Environment* 2020;715:136948.
<https://doi.org/10.1016/j.scitotenv.2020.136948>.
- [159] Pieroni MPP, McAloone TC, Pigosso DCA. Business model innovation for circular economy and sustainability: A review of approaches. *J Clean Prod* 2019;215:198–216. <https://doi.org/10.1016/j.jclepro.2019.01.036>.
- [160] Pieroni MPP, McAloone TC, Borgianni Y, Maccioni L, Pigosso DCA. An expert system for circular economy business modelling: advising manufacturing companies in decoupling value creation from resource consumption. *Sustain Prod Consum* 2021;27:534–50.
<https://doi.org/10.1016/j.spc.2021.01.023>.
- [161] Morse S, Morse S. *Post-Sustainable Development* 2008;352:341–52.
- [162] Ruggerio CA. Sustainability and sustainable development: A review of principles and definitions. *Science of the Total Environment* 2021;786:147481. <https://doi.org/10.1016/j.scitotenv.2021.147481>.
- [163] Purvis B, Mao Y, Robinson D. Three pillars of sustainability: in search of conceptual origins. *Sustain Sci* 2019;14:681–95.
<https://doi.org/10.1007/s11625-018-0627-5>.
- [164] Nilsson M, Griggs D, Visbeck M, Ringler C. A Draft Framework for Understanding SDG Interactions. *Chemistry International* 2016;38.
<https://doi.org/10.1515/ci-2016-0632>.
- [165] Al-Surf M, Balabel A, Alwetaishi M, Abdelhafiz A, Issa U, Sharaky I, et al. Stakeholder's perspective on green building rating systems in Saudi Arabia: The case of LEED, Mostadam, and the SDGS. *Sustainability (Switzerland)* 2021;13. <https://doi.org/10.3390/su13158463>.
- [166] Castro-Lacouture D, Sefair JA, Flórez L, Medaglia AL. Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. *Build Environ* 2009;44:1162–70.
<https://doi.org/10.1016/j.buildenv.2008.08.009>.
- [167] Teng J, Mu X, Wang W, Xu C, Liu W. Strategies for sustainable development of green buildings. *Sustain Cities Soc* 2019;44:215–26.
<https://doi.org/10.1016/j.scs.2018.09.038>.
- [168] Arrigoni A, Panesar DK, Duhamel M, Opher T, Saxe S, Posen ID, et al. Life cycle greenhouse gas emissions of concrete containing supplementary cementitious materials: cut-off vs. substitution. *J Clean Prod* 2020;263:121465. <https://doi.org/10.1016/j.jclepro.2020.121465>.
- [169] Goubran S, Cucuzzella C. Integrating the Sustainable Development Goals in Building Projects. *Journal of Sustainability Research* 2019;1.
<https://doi.org/10.20900/jsr20190010>.

- [170] Zastrow P, Molina-Moreno F, García-Segura T, Martí J V., Yepes V. Life cycle assessment of cost-optimized buttress earth-retaining walls: A parametric study. *J Clean Prod* 2017;140:1037–48.
<https://doi.org/10.1016/j.jclepro.2016.10.085>.
- [171] Agbesi K, Fugar FD, Adjei-Kumi T. Modelling the adoption of sustainable procurement in construction organisations. *Built Environment Project and Asset Management* 2018;8:461–76.
<https://doi.org/10.1108/BEPAM-10-2017-0108>.
- [172] Wen B, Musa SN, Onn CC, Ramesh S, Liang L, Wang W, et al. The role and contribution of green buildings on sustainable development goals. *Build Environ* 2020;185:107091.
<https://doi.org/10.1016/j.buildenv.2020.107091>.
- [173] Secher AQ, Collin C, Linnet A. Construction Product Declarations and Sustainable Development Goals for Small and Medium Construction Enterprises. *Procedia CIRP* 2018;69:54–8.
<https://doi.org/10.1016/j.procir.2017.12.011>.
- [174] Omer MAB, Noguchi T. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). *Sustain Cities Soc* 2020;52:101869.
<https://doi.org/10.1016/j.scs.2019.101869>.
- [175] Burgass MJ, Halpern BS, Nicholson E, Milner-Gulland EJ. Navigating uncertainty in environmental composite indicators. *Ecol Indic* 2017;75:268–78. <https://doi.org/10.1016/j.ecolind.2016.12.034>.
- [176] Anastasiou EK, Liapis A, Papayianni I. Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resour Conserv Recycl* 2015;101:1–8.
<https://doi.org/10.1016/j.resconrec.2015.05.009>.
- [177] Marinković S, Dragaš J, Ignjatović I, Tošić N. Environmental assessment of green concretes for structural use. *J Clean Prod* 2017;154:633–49.
<https://doi.org/10.1016/j.jclepro.2017.04.015>.
- [178] Borghi G, Pantini S, Rigamonti L. Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). *J Clean Prod* 2018;184:815–25.
<https://doi.org/10.1016/j.jclepro.2018.02.287>.
- [179] Atmaca A, Atmaca N. Life cycle energy (LCEA) and carbon dioxide emissions (LCCO₂A) assessment of two residential buildings in Gaziantep, Turkey. *Energy Build* 2015;102:417–31.
<https://doi.org/10.1016/j.enbuild.2015.06.008>.

- [180] Guo Z, Tu A, Chen C, Lehman DE. Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates. *J Clean Prod* 2018;199:136–49. <https://doi.org/10.1016/j.jclepro.2018.07.069>.
- [181] Rajabi S, El-Sayegh S, Romdhane L. Identification and assessment of sustainability performance indicators for construction projects. *Environmental and Sustainability Indicators* 2022;15:100193. <https://doi.org/10.1016/j.indic.2022.100193>.
- [182] Sharma R, Jang JG, Hu JW. Phase-Change Materials in Concrete: Opportunities and Challenges for Sustainable Construction and Building Materials. *Materials* 2022;15. <https://doi.org/10.3390/ma15010335>.
- [183] Opon J, Henry M. An indicator framework for quantifying the sustainability of concrete materials from the perspectives of global sustainable development. *J Clean Prod* 2019;218:718–37. <https://doi.org/10.1016/j.jclepro.2019.01.220>.
- [184] Kurda R, Silvestre JD, de Brito J. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. *Resour Conserv Recycl* 2018;139:407–17. <https://doi.org/10.1016/j.resconrec.2018.07.004>.
- [185] Alami AH, Olabi AG, Ayoub M, Aljaghoub H, Alasad S, Abdelkareem MA. 3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals. *Buildings* 2023;13. <https://doi.org/10.3390/buildings13040924>.
- [186] Onuoha IJ, Aliagha GU, Rahman MSA. Modelling the effects of green building incentives and green building skills on supply factors affecting green commercial property investment. *Renewable and Sustainable Energy Reviews* 2018;90:814–23. <https://doi.org/10.1016/j.rser.2018.04.012>.
- [187] Sullivan K, Thomas S, Rosano M. Using industrial ecology and strategic management concepts to pursue the Sustainable Development Goals. *J Clean Prod* 2018;174:237–46. <https://doi.org/10.1016/j.jclepro.2017.10.201>.
- [188] Gilfillan D, Marland G. CDIAC-FF: Global and national CO₂ emissions from fossil fuel combustion and cement manufacture: 1751-2017. *Earth Syst Sci Data* 2021;13:1667–80. <https://doi.org/10.5194/essd-13-1667-2021>.
- [189] Kim Y, Worrell E. CO₂ emission trends in the cement industry: An international comparison. *Mitig Adapt Strateg Glob Chang* 2002;7:115–33. <https://doi.org/10.1023/A:1022857829028>.

- [190] Andrew, R. MGlobal CO 2 emissions from cement production, 1928–2017. *Earth System Science Data*; 2018 10(4), 2213-2239.
<https://doi.org/10.5281/zenodo.831454>.
- [191] Nie, S., Zhou, J., Yang, F., Lan, M., Li, J., Zhang, Z., ... & Sanjayan, J. G. Analysis of theoretical carbon dioxide emissions from cement production: Methodology and application. *Journal of Cleaner Production*; 2022; 334, 130270.
- [192] Taylor M, Tam C, Gielen D. Energy Efficiency and CO 2 Emissions from the Global Cement Industry Energy Efficiency and CO 2 Emission Reduction Potentials and Policies in the Cement 2006:4–5.
- [193] Sterman J. systems thinking and modeling for a complex world. *Instructor's Manual to Accompany Business Dynamics*: McGraw-Hill 2000.
- [194] Le Blanc D. Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustainable Development* 2015;23:176–87. <https://doi.org/10.1002/sd.1582>.
- [195] Nilsson M, Chisholm E, Griggs D, Howden-Chapman P, McCollum D, Messerli P, et al. Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustain Sci* 2018;13:1489–503. <https://doi.org/10.1007/s11625-018-0604-z>.
- [196] Khafagy MES, El-Sayed H, Darwish KM. Land cover/use change analysis and mapping of Borg El-Arab City, Egypt. *Arabian Journal of Geosciences* 2020;13. <https://doi.org/10.1007/s12517-020-06115-x>.
- [197] New Urban Communities Authority. New Urban Communities Authority Portal". New Cities Government of Egypt. Retrieved 20 November 2021. 2021.
- [198] New Borg Elarab city. New Borg Elarab city. Google Map 2022. <https://goo.gl/maps/EcxDWZxwVKHMdhXh6>.
- [199] Communities Authority (NUCA) 2010. Official Publication of the New Cairo city, New Urban. 2010.
- [200] The World Bank. Towards an urban sector strategy (Vol. 2). Sustainable Development Department Middle East and North Africa Region 2008;2:129.
- [201] Sharkawi AE-DM, Almoftly SE-DM, Abbass EngSM. Performance of Green Aggregate Produced by Recycling Demolition Construction Wastes (Case Study of Tanta City). *Engineering* 2016;08:52–9. <https://doi.org/10.4236/eng.2016.82006>.
- [202] Wagih AM, El-Karmoty HZ, Ebid M, Okba SH. Recycled construction and demolition concrete waste as aggregate for structural concrete.

- HBRC Journal 2013;9:193–200.
<https://doi.org/10.1016/j.hbrcj.2013.08.007>.
- [203] HBRC. Arabic. Egyptian Code of Practice for Concrete Structures,. ,
 Cairo, Egypt.: 2007.
- [204] Abdel Raheem, S. E. (Evaluation of Egyptian code provisions for
 seismic design of moment-resisting-frame multi-story
 buildings. International Journal of Advanced Structural Engineering,
 2013; 5, 1-18. <https://doi.org/10.1186/2008-6695-5-20>
- AM, El-Karmoty HZ, Ebid M, Okba SH. Recycled construction and demolition
 concrete waste as aggregate for structural concrete. HBRC Journal
 2013;9:193–200. <https://doi.org/10.1016/j.hbrcj.2013.08.007>.
- [205] Bildirici ME. Cement production, environmental pollution, and
 economic growth: evidence from China and USA. Clean Technol
 Environ Policy 2019;21:783–93. <https://doi.org/10.1007/s10098-019-01667-3>.
- [206] Hammond GP, Jones CI. Embodied energy and carbon in construction
 materials. Proceedings of Institution of Civil Engineers: Energy
 2008;161:87–98. <https://doi.org/10.1680/ener.2008.161.2.87>.
- [207] Homer J. Best practices in system dynamics modeling, revisited: a
 practitioner’s view. Syst Dyn Rev 2019;35:177–81.
<https://doi.org/10.1002/sdr.1630>.
- [208] Yang KH, Jung YB, Cho MS, Tae SH. Effect of supplementary
 cementitious materials on reduction of CO2 emissions from concrete. J
 Clean Prod 2015;103:774–83.
<https://doi.org/10.1016/j.jclepro.2014.03.018>.
- [209] Ismail EHR, El-Mahdy GM, Ibrahim AH, Daoud AO. Analysis of factors
 affecting construction and demolition waste safe disposal in Egypt.
 Alexandria Engineering Journal 2023;70:515–23.
<https://doi.org/10.1016/j.aej.2023.03.012>.
- [210] Ali RK, Mousa MG, Sheta SA. Communities in Egypt 2020;45.
- [211] Hegazy IR. Urban strategies and environmental policy: Towards urban
 sustainability within the Egyptian context. Environ Dev 2014;11:190–
 207. <https://doi.org/10.1016/j.envdev.2014.05.002>.
- [212] Ebrahim Abu El-Maaty Behiry A. Utilization of cement treated recycled
 concrete aggregates as base or subbase layer in Egypt. Ain Shams
 Engineering Journal 2013;4:661–73.
<https://doi.org/10.1016/j.asej.2013.02.005>.

- [213] El-Shennawy A, Boros V, Novak B. Comparison between the Provisions of the Egyptian Code of Practice and the Eurocodes for Reinforced Concrete Structures Design. World SB14 Barcelona 2014;1–7.
- [214] Khalil EA. Impact of autoclaved aerated concrete (AAC) on modern constructions: A case study in the new Egyptian administrative capital 2019;14:184.
- [215] Latif AA, Magdy D, Sharkawy K El, William M, ... Egypt SDS 2030: Between Expectations and Challenges to Implement/ 2018.
- [216] Tan Y, Shuai C, Shen L, Hou L, Zhang G. A study of sustainable practices in the sustainability leadership of international contractors. Sustainable Development 2020;28:697–710.
<https://doi.org/10.1002/sd.2020>.
- [217] Silva R V., de Brito J, Dhir RK. Use of recycled aggregates arising from construction and demolition waste in new construction applications. J Clean Prod 2019;236:117629.
<https://doi.org/10.1016/j.jclepro.2019.117629>.
- [218] Shan X, Zhou J, Chang VWC, Yang EH. Life cycle assessment of adoption of local recycled aggregates and green concrete in Singapore perspective. J Clean Prod 2017;164:918–26.
<https://doi.org/10.1016/j.jclepro.2017.07.015>.
- [219] Hafez H, Kurda R, Al-Ayish N, Garcia-Segura T, Cheung WM, Nagaratnam B. A whole life cycle performance-based ECONomic and ECOlogical assessment framework (ECO2) for concrete sustainability. J Clean Prod 2021;292:126060
[.https://doi.org/10.1016/j.jclepro.2021.126060](https://doi.org/10.1016/j.jclepro.2021.126060)
- [220] Elahi, A., Basheer, P. A. M., Nanukuttan, S. V., & Khan, Q. U. Z. (2010). Mechanical and durability properties of high-performance concrete containing supplementary cementitious materials. Construction and Building Materials, 24(3), 292-299.
- [221] Younes A, Elbeltagi E, Diab A, Tarsi G, Saeed F, Sangiorgi C. Incorporating coarse and fine recycled aggregates into concrete mixes: mechanical characterization and environmental impact. J Mater Cycles Waste Manag 2023. <https://doi.org/10.1007/s10163-023-01834-1>.
- [222] Kleijer AL, Lasvaux S, Citherlet S, Viviani M. Product-specific Life Cycle Assessment of ready mix concrete: Comparison between a recycled and an ordinary concrete. Resour Conserv Recycl 2017;122:210–8. <https://doi.org/10.1016/j.resconrec.2017.02.004>.
- [223] Biswas WK, Alhorr Y, Lawania KK, Sarker PK, Elsarrag E. Life cycle assessment for environmental product declaration of concrete in the Gulf

States. *Sustain Cities Soc* 2017;35:36–46.

<https://doi.org/10.1016/j.scs.2017.07.011>.

- [224] Braga AM, Silvestre JD, de Brito J. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *J Clean Prod* 2017;162:529–43. <https://doi.org/10.1016/j.jclepro.2017.06.057>.
- [225] Van Den Heede P, De Belie N. Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. *Cem Concr Compos* 2012;34:431–42. <https://doi.org/10.1016/j.cemconcomp.2012.01.004>.
- [226] Braulio-Gonzalo M, Jorge-Ortiz A, Bovea MD. How are indicators in Green Building Rating Systems addressing sustainability dimensions and life cycle frameworks in residential buildings? *Environ Impact Assess Rev* 2022;95:106793. <https://doi.org/10.1016/j.eiar.2022.106793>.
- [227] Huo X, Yu ATW, Darko A, Wu Z. Critical factors in site planning and design of green buildings: A case of China. *J Clean Prod* 2019;222:685–94. <https://doi.org/10.1016/J.JCLEPRO.2019.03.123>.
- [228] Fan C, Miller SA. Reducing greenhouse gas emissions for prescribed concrete compressive strength. *Constr Build Mater* 2018;167:918–28. <https://doi.org/10.1016/j.conbuildmat.2018.02.092>.
- [229] Huo X, Yu ATW, Wu Z. An empirical study of the variables affecting site planning and design in green buildings. *J Clean Prod* 2018;175:314–23. <https://doi.org/10.1016/J.JCLEPRO.2017.12.091>.
- [230] Scope, C., Vogel, M., & Guenther, E. (2021). Greener, cheaper, or more sustainable: Reviewing sustainability assessments of maintenance strategies of concrete structures. *Sustainable Production and Consumption*, 26, 838-858. <https://doi.org/10.1016/j.spc.2020.12.022>
- [231] Moldan B, Janoušková S, Hák T. How to understand and measure environmental sustainability: Indicators and targets. *Ecol Indic* 2012;17:4–13. <https://doi.org/10.1016/j.ecolind.2011.04.033>.
- [232] Braulio-Gonzalo M, Jorge-Ortiz A, Bovea MD. How are indicators in Green Building Rating Systems addressing sustainability dimensions and life cycle frameworks in residential buildings? *Environ Impact Assess Rev* 2022;95:106793. <https://doi.org/10.1016/j.eiar.2022.106793>.
- [233] Olakitan Atanda J. Developing a social sustainability assessment framework. *Sustain Cities Soc* 2019;44:237–52. <https://doi.org/10.1016/j.scs.2018.09.023>.
- [234] Fatourehchi D, Zarghami E. Social sustainability assessment framework for managing sustainable construction in residential buildings. *Journal of*

- Building Engineering 2020;32:101761.
<https://doi.org/10.1016/j.jobbe.2020.101761>.
- [235] Sangwan KS, Bhakar V, Digalwar AK. A sustainability assessment framework for cement industry – a case study. *Benchmarking* 2019;26:470–97. <https://doi.org/10.1108/BIJ-01-2018-0021>.
- [236] Abouhamad M, Abu-Hamd M. Life cycle assessment framework for embodied environmental impacts of building construction systems. *Sustainability (Switzerland)* 2021;13:1–21.
<https://doi.org/10.3390/su13020461>.
- [237] Reddy AS, Kumar PR, Raj PA. Preference based multi-criteria framework for developing a Sustainable Material Performance Index (SMPI). *International Journal of Sustainable Engineering* 2019;12:390–403. <https://doi.org/10.1080/19397038.2019.1581853>.
- [238] Figueiredo K, Pierott R, Hammad AWA, Haddad A. Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. *Build Environ* 2021; 196:107805. <https://doi.org/10.1016/j.buildenv.2021.107805>.

APPENDIX

Table15. Green Concrete Material Sustainability Indicators GCM-SI Contribution to three sustainability pillars and the SDGs.

Environmental									
SDGs	GHG	Waste	Water	Global warming	Pollution	Energy	CO ₂	Cement	Resources
SDG1									
SDG2									
SDG3									
SDG4									
SDG5									
SDG6									
SDG7									
SDG8									
SDG9									
SDG10									
SDG11									
SDG12									
SDG13									
SDG14									
SDG15									
SDG16									
SDG17									
Social									
	Aesthetic	Maintenance	Safety	Affordability	Community	Human Health	Comfort Level	New Job	Lifespan
SDG1									
SDG2									
SDG3									
SDG4									
SDG5									
SDG6									
SDG7									
SDG8									
SDG9									
SDG10									
SDG11									
SDG12									
SDG13									
SDG14									
SDG15									
SDG16									
SDG17									
Economic									
	Project Cost	materials Cost	Transport	Energy Saving	Property Value	Disposal Cost	Durability	Strength	Labor Cost
SDG1,									
SDG2									
SDG3									
SDG4									
SDG5									
SDG6									
SDG7									
SDG8									
SDG9									
SDG10									
SDG11									
SDG12									

SDG13									
SDG14									
SDG15									
SDG16									
SDG17									

“Dark yellow Color (very low), light yellow (Low), grey (moderate), light green (high), and dark green (very high)” are the levels of contribution between the GCM indicators and each SDGs.

Very low	Low	Moderate	High	Very high
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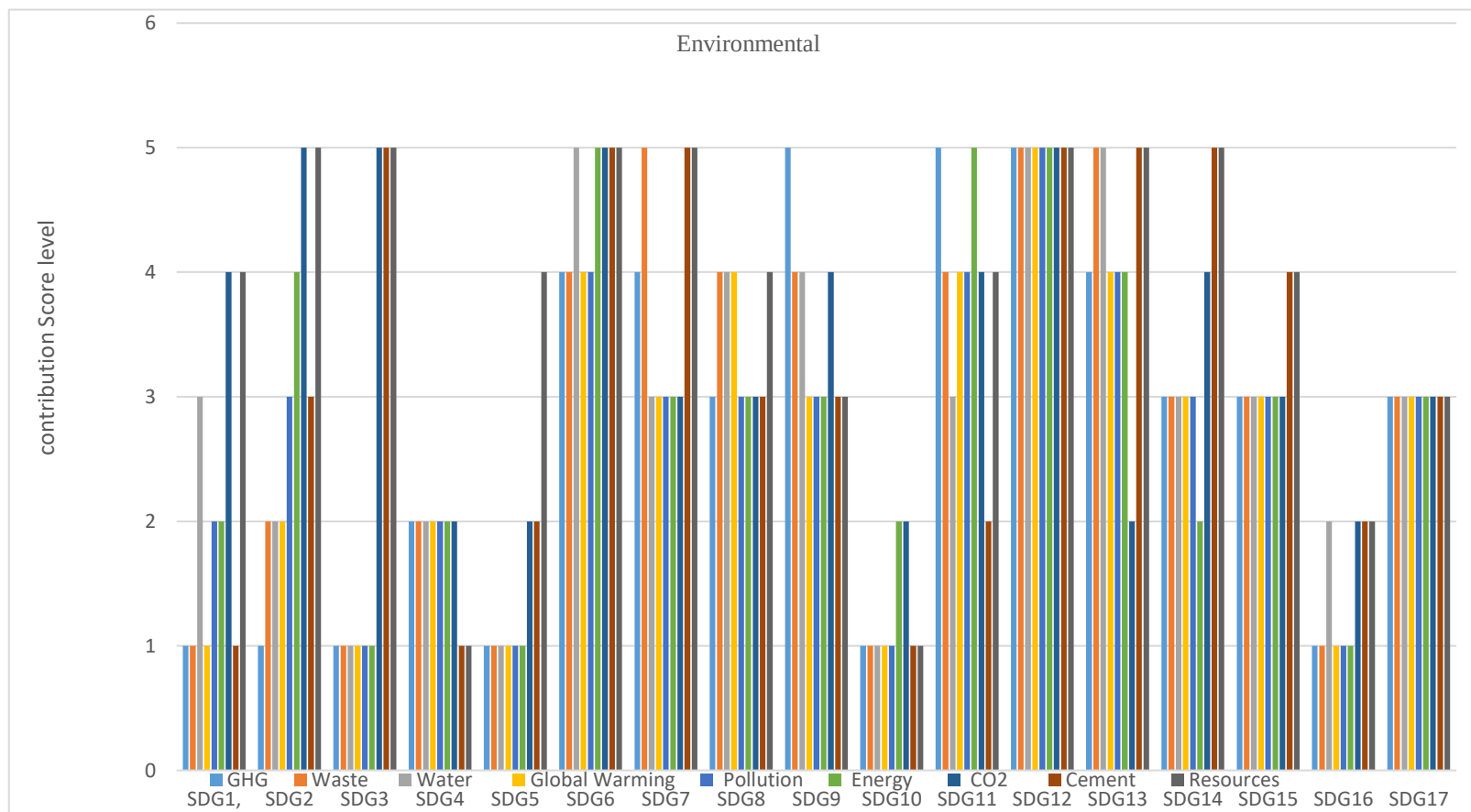


Figure A1 Green Concrete Material Sustainability Indicators GCM-SI Contribution to environmental pillar and the SDGs.

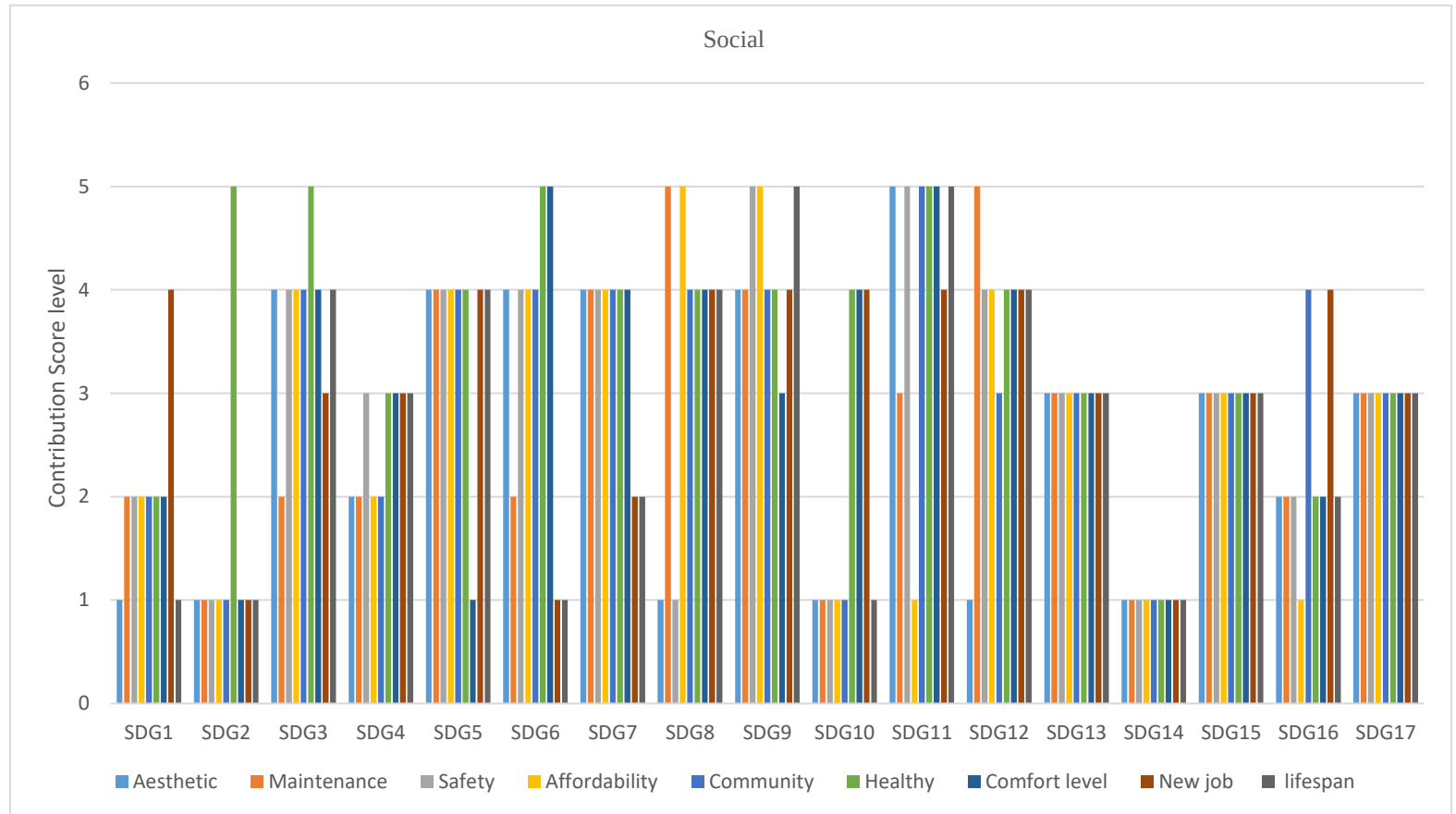


Figure A2 Green Concrete Material Sustainability Indicators GCM-SI Contribution to social pillar and the SDGs.

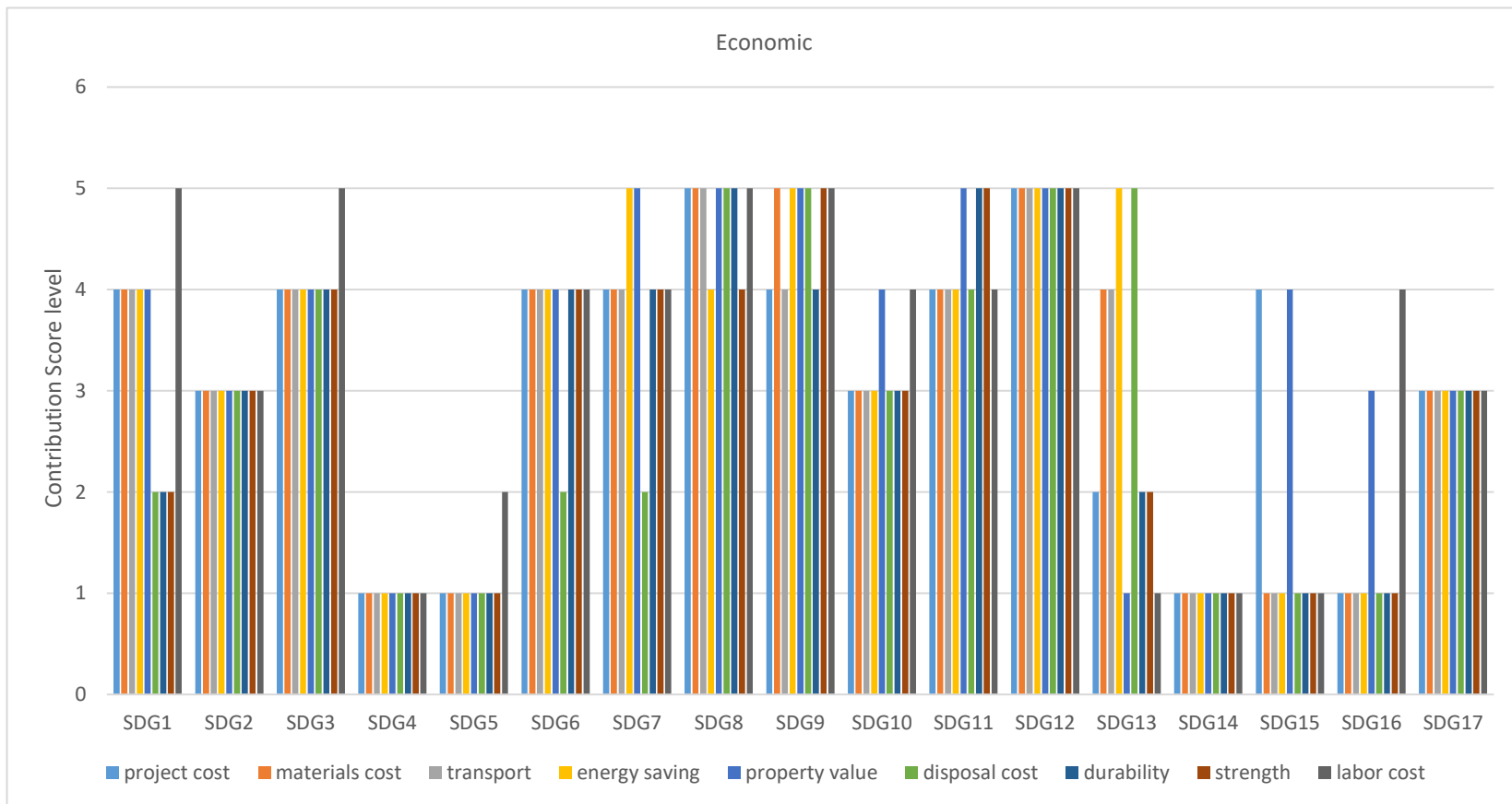


Figure A3 Green Concrete Material Sustainability Indicators GCM-SI Contribution to Economic Pillar and the SDGs.