

Green concrete materials selection for achieving circular economy in residential buildings using system dynamics

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ABSTRACT

Increasing the number of residential buildings due to rapid urbanization growth has led to the massive consumption of concrete materials and significant negative environmental impacts worldwide. Properly selecting green concrete (GC) materials in residential projects can promote sustainable construction practices and achieve a circular economy (CE). This paper aims to identify and analyze the parameters affecting GC material selection based on CE principles by developing a system dynamic (SD) model to investigate the environmental and economic benefits during the construction process. The system dynamic-based framework (SD-BF) is used to investigate the simulation interaction of the variables between the GC original scenario and several hypothetical scenarios through the simulation process, including fly ash concrete (FA) and recycled aggregate concrete (RAC). The causal loop diagrams (CLD) and stock and flow (SF) diagrams are created to investigate the inner relations among the GC variables that can achieve CE. The SD model was applied for a residential building case study in New Cairo City, Egypt, using Vensim to simulate and analyse the most appropriate GC scenarios regarding cement, natural aggregate, CO₂ emissions, cost-effectiveness, and waste generation. The results showed that using various concrete scenarios could enhance the GC selection for CE principles, in which cement reduction is the most effective variable, and the reduction reached 19.8% and 11.4% in the most optimum scenarios, while the natural aggregate (NA) reduction reached 19.1% compared with the original scenario. This development is vital for achieving CE and closing the concrete materials loop, which helps construction decision-makers select suitable concrete materials for future residential projects.

1. Introduction

1.1. The construction and residential building industry

Population growth and urbanization resulted in an increasing number of new residential buildings and a rapid consumption rate of construction materials worldwide (Habitat, 2022). The raw materials used in cement and concrete production are essential for the construction and building sector, and the continuous extensive consumption of these

resources may result in a supply shortage and prevent sustainability in the future (Habert et al., 2020). Therefore, achieving CE in the construction of the residential building sector has tremendous attention and has become significant for achieving sustainability. Since the United Nations Habit estimated that three billion people, approximately 40 % of the world's population, will live in housing by 2030, the demand for residential building numbers will increase to reach approximately 96,000 new housing units per day globally (Habitat, 2022). This will be followed by increasing the average house floor area, which leads to

Abbreviations: OPC, Ordinary Portland Cement; GC, Green Concrete; CC, Conventional Concrete; RAC, Recycled Aggregate Concrete; RCA, Recycled Concrete Aggregates D; BOQ, Bill Of Quantity; NCA, Natural Coarse Aggregates; CDW, Construction and Demolition; CE, Circular Economy; SD-BF, System Dynamic-Based Framework Model; FA, Fly Ash; SCMs, Supplementary Cementitious Materials; SD, System Dynamic; RA, Recycled Aggregate Materials; GGBFS, Ground Granulated Blast Furnace Slag; PCC-R, Portland Cement Concrete Reinforced; PCC-N, Portland Cement Concrete Non-reinforced; FA-R, Fly ash concrete reinforced; FA-N, Fly Ash Concrete Non-Reinforced; RAC-N, Recycled Aggregate Concrete Non-reinforced; LEED, Leadership in Energy and Environmental Design; BREEAM, Building Research Establishment Environmental Assessment Method; GPRS, Green Pyramids Rating System; RC, Reinforced Concrete; CLD, Causal Loop Diagram; SF, Stock and Flow Diagram.

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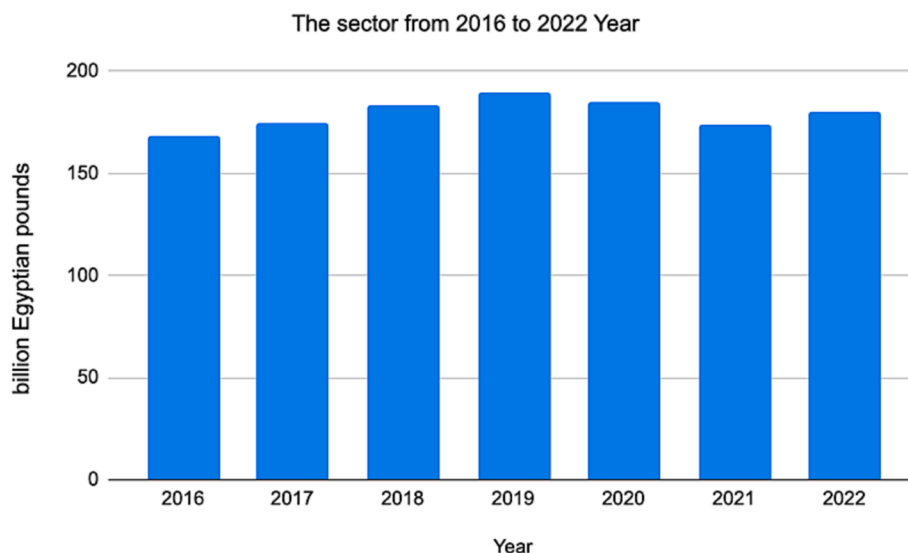


Fig. 1. The construction sector investment from 2016 to 2022 based on (Statistics, E. 2023).

massive materials consumption associated with massive energy use, CO₂ emission, and waste generation. However, the building industry was responsible for 38 % and 14 GT of energy-related greenhouse gas (GHG) emissions and consumed 16 % of freshwater (Baynes et al., 2018; Ding, G. K., 2014). For example, the construction of new building projects causes more than 50 % of emissions based on embodied carbon, and 70 % comes from six construction materials, such as concrete and steel (Meyer, 2009; Nilimaa, 2023).

In 2018, in Latin America and Africa, the buildings & construction industry accounted for (24 % of 21 %), and (61 % and 32 %) of the final energy and CO₂ emissions; meanwhile, China, & India accounted for 27 % of 24 % of the regional energy and CO₂ emissions, and all the previous without accounting for the building materials manufacturing (IEA, 2019; Global ABC/IEA/UNEP 2020b; Romo-Orozco et al., 2022). On the other side, the indicators of global decarbonization trajectories still referred that the industry should reduce emissions by 50 % by 2030 to reach net zero and achieve the Paris Agreement climate goals (WBCSD and ARUP, 2021). Consequently, the sector is considered one of the most critical three sectors that can achieve CE and improve sustainability; for instance, in Europe, applying sustainable construction materials is expected to influence 42 % of final energy consumption, about (35 %) of GHG emissions, and about 50 % of extracted raw materials (Favier et al., 2018; Abouhamad & Abu-Hamd, 2021), additionally to save 30 % water consumption based on the roadmap for resource-efficient in Europe (Bobbà et al., 2020), (IEA & UNEP, 2018) (Miller, Horvath, et al., 2018).

The residential Egyptian construction sector is considered the highest energy and raw construction materials consumption. According to the 2020/2021 report of (Electricity Holding Company), the residential buildings' electricity consumption reached 40.5 %, while commercial buildings recorded 13 %, indicating the high energy consumption rate used for this sector. On the other side, the sector is essential to national economic growth, considered one of the most 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, based on the Central Agency for Public Mobilization and Statistics (CAPMAS) (Statistics, E. 2023). Hence, the Egyptian construction sector contributed to the GDP growth, which increased from 6.3 % to 6.8 % for the years (2018–2019) & (2020–2021) respectively (Emad et al., 2023). The government's economic reform program was established in 2016 to face the challenges of the continuous increase of population growth, and the investment of the residential sector reached 865 billion (LE) Egyptian pounds between 2016 and 2022, as shown in Fig. 1, which is approximately 173 billion

LE per year. The Egyptian government has paid attention to the construction sector to meet market needs for new residential buildings and achieve the urban quality of life in Egypt Vision 2030 (HBRC Arabic, 2023).

1.2. Concrete & green concrete

Concrete is considered the most used man-made material, and Portland cement concrete (PCC) is a common and widely used material in construction activities worldwide. However, cement accounts for 10–15 % of the PCC volume; global cement production reached 4.1 billion tons in 2022 (Garside, M., 2019) and is estimated to continuously increase the global demand for construction activity in the next decades (Schneider et al., 2023). This indicates that average cement consumption per capita will increase in the coming years due to increased buildings and infrastructure projects worldwide (Miller, Horvath, et al., 2018). Cement manufacturing contributed nearly 7 % to anthropogenic GHG emissions, about 8 % of the global CO₂ (Scrivener et al., 2018), and is expected to increase by 40 % by the year 2050 if no reduction measures are taken (Schneider et al., 2023). Whereas one ton of cement caused approximately 0.9 tons of carbon footprint. Due to it has massive and wide consumption, cement is considered the second most polluting material globally (Habert et al., 2020; IEA, 2016).

Therefore, decarbonizing the concrete and cement industry as a driver became crucial when cement contributes approximately more than 70 % of the construction industry's GHG emissions (Miller, Horvath, et al., 2018; Habert et al., 2020; Miller et al., 2016; Schneider et al., 2011). Supplementary cementitious materials (SCMs) are one of the most important solutions for eliminating environmental impacts by reducing the total cement consumption and concrete materials. This helps decrease the total CO₂ emissions produced during clinker production (Komkova & Habert, 2023; Habert et al., 2020; Barcelo et al., 2014). However, the cement industry has grown fast in the past decades due to the growing demand for concrete materials worldwide (Miller John et al., 2018; UNFCCC, 2015), but the industry recommended reducing its direct emissions GHG by least 24 % compared to current levels by 2050 to have a > 50 % chance of keeping the global average temperature rise below 2 °C (IEA, 2016; Assi et al., 2020; Müller et al., 2014). Due to the massive increase in the consumption of raw materials for CC components like cement, water, and aggregates, the depletion of natural resources has driven awareness toward GC materials as a sustainable solution.

1.2.1. Green concrete

Sustainable concrete is an essential starting point, offers opportunities in the early design stage, and enhances the residential projects' environmental, economic, and social aspects (Marey et al., 2022).

GC is defined as concrete that contains recycled materials in its components or/and has an environment-friendly manufacturing process and has a high performance during the building's life cycle (Suhendro, 2014; Sivakrishna et al., 2019). Due to the massive increase in the consumption of raw materials for CC components like cement, water, and aggregates, the depletion of natural resources has driven awareness toward sustainable solutions. Thereby, in the past few years, noticed that the new generation of GC composites increased by producing concrete mixtures with various SCMs, such as industrial, agriculture-farming, and municipal wastes. Therefore, the use of recycling industrial by-products such as FA, including calcareous and siliceous, silica fume (SF), and ground granulated blast furnace slag (GGBFS) in the concrete sector is a viable choice for sustainability (Hemalatha & Ramaswamy, 2017). Additionally, the substitute recycling municipal waste, such as construction and demolition waste (CDW), and reused as a portion of NA, is considered an eco-friendly material (Lothenbach et al., 2011; Paris et al., 2016). According to various scholars, GC's strength, durability, workability, and fire resistance increased by optimizing the properties of recycled materials when used as alternative cementitious materials for reducing CC component emissions (Cuenca-Moyano et al., 2023a; Yehia et al., 2015; Aprianti S, 2017; Golewski, 2018). However, compressive strength is considered the most critical parameter of GC materials, which is dependent on the concrete ratio component, cement type, and aggregate properties to determine the concrete type and function. So, the variety and availability of GC materials can improve the concrete material's properties and enhance the final project cost for the residential building sector (Błaszczynski & Król, 2015). Comparing several different materials, it was reported that the GC considers more environmentally sustainable materials with the same functionalities and properties as CC, and it can reduce negative environmental impacts in terms of CO₂ emissions, natural resources, and cost-effectiveness. Thereby, GC has the potential to meet the CE core principles and achieve sustainable development's environmental and economic objectives (Liew et al., 2017; Zhang et al., 2019). As a result, there is still much room for innovation and development methods that provide opportunities to improve concrete's use of natural resources.

1.2.1.1. Recycled aggregate concrete (RAC). Recycling concrete presents a sustainable solution for reusing CDW and has become a common practice worldwide. The USA reached around 50 % of concrete debris and mixed rubble, considered a valuable alternative for recycling and reusing as aggregates. (de Juan & Gutiérrez, 2009) Therefore, using CDW, such as recycled Aggregate materials (RA) for producing recycled aggregate concrete (RAC), could enhance environmental and economic benefits (Al-Gahtani et al., 2017; Liew et al., 2017). The natural coarse aggregate (NCA) replacement achieves cost-effectiveness when replaced with recycled concrete aggregate (RCA) to produce the RAC that, after the proper treatment and control of the particle size distribution, enhances the RAC quality for maintaining concrete compressive strength (Tam et al., 2018; Al-Mansour et al., 2019). For example (El-Hawary et al., 2021) showed that the mechanical properties of concrete contain RCA by 25 % and 100 %, affecting the mechanical strength by reducing 5 % and 25 %, respectively, and by examining the RAC quality was increased with the total replacement of NCA to a strength of (35 MPa) with a fixed ratio of water-to-cement 0.48 for all the concrete mixes (HBRC Arabic, 2007; Rahal, 2007; Thomas et al., 2013).

Therefore, the materials are applied to general purposes of construction works, such as pavements and roadways, in moderate conditions (Błaszczynski & Król, 2015). Conversely, the high replacement of NA with RCA can affect the concrete mechanical properties regarding flexural strength, porosity, and water absorption. In contrast, the

replacement slowly affects durability and should be considered and evaluated by the same CC materials (Duan et al., 2020; Marvila et al., 2022; Robalo et al., 2021). Various previous challenges for physical properties were faced due to the significant regional differences of RA components. However, the concretes containing less than 50 % of mixed RCA, the compressive as well as flexure strength do not change considerably (Cantero et al., 2021; Joseph et al., 2022; Pacheco & de Brito, 2021).

In the case of using the recycling CDW for mortar production, (Azevedo et al., 2020) evaluated and discussed the properties of the hardened mortar states after the partial and total substitution of natural sand and investigated four mortar mixtures. They found that applying the CDW enhances the compaction degree and increases the mortar's compressive strength. Still, to reach the mortar's standards and requirements, the natural sand replacement shouldn't exceed 25 % to avoid increasing water use (Colangelo et al., 2018; Makul et al., 2021; Marvila et al., 2022; Azevedo et al., 2020). Therefore, the characteristics and applications need more investigation and development, especially in the residential building sector (Al-Mansour et al., 2019) (Błaszczynski & Król, 2015; Halahla et al., 2019) (de Juan & Gutiérrez, 2009; Shmlls et al., 2023), (Berndt, 2009).

1.2.1.2. Fly ash. Coal is considered a significant source of electricity production worldwide. Thereby its combustion process causes adverse environmental impacts and generates a large quantity of FA. It is defined as by-product materials from coal-based power stations resulting from coal combustion (Golewski, 2018; Hemalatha & Ramaswamy, 2017), and started using FA in concrete in the late 20th century. Despite the movement to replace fossil fuels with sustainable energy sources such as wind, solar, and biogas, recently increasing energy demand has led to heavy reliance on coal-fired power plants worldwide (Oleksik et al., 2023). Consequently, the advantages and disadvantages have been widely researched as a step forward to mitigate the waste disposal problem due to the increasing usage of FA in various fields. In the concrete industry, it was used as partial cement replacement, which improves compressive strength and durability. It contributes to reducing CO₂ emissions and energy consumption and is considered a clean production solution for eliminating the exploitation of natural resources (Deng et al., 2022). Furthermore, substituting ordinary Portland cement (OPC) with FA partially reduces industrial solid waste disposal, decreasing cement consumption and increasing concrete performance. (Cuenca-Moyano et al., 2023b; Velenturf & Purnell, 2021). This improves the cost and conserves natural resources at the local, regional, and global levels (Hemalatha & Ramaswamy, 2017). Based on the CE core principles that recommended reducing waste, using FA is considered a sustainable option and provides a circularity benefit for concrete production by efficiently using resources to close the materials' loop through the recycling process of the waste materials and reuse them as new materials sources (Teixeira et al., 2016). Therefore, FA can replace cement from 20 % to 60 % in low and high volumes of concrete materials, respectively, and is suitable for various applications (Saldarriaga et al., 2022). The FA concrete is higher than the OPC in long-term strength, so it can be used in several structural engineering applications.

Meanwhile, the FA has disadvantages, such as varying quality based on the source, slow pozzolanic reaction, dark gray color, increasing transportation costs, and limiting availability and use in rural and suburban areas. Therefore, considering the residential building project requirements is crucial for properly using FA and applying CE and sustainability in the construction industry. Thereby, it can allow for decoupling urbanization and economic growth through reducing continuous extraction and consumption of natural resources, providing a more sustainable model in the residential building sector. The efficient use of resources to close the materials' loop through the recycling process of waste materials by reusing them as new materials sources and maximizing their value (Teixeira et al., 2016). Despite the slow

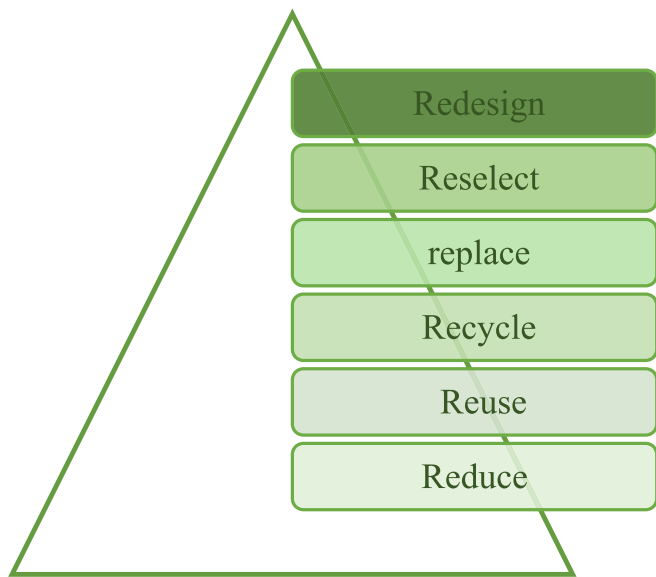


Fig. 2. Circular economy core principles for green concrete (Marey et al., 2022; Marsh et al., 2022).

pozzolanic reaction, the concrete campsites contain a high FA proportion, increasing the compressive strength compared to the CC mix (Ahmad et al., 2021; Huang et al., 2013), which indicates the applicability for use in residential applications.

In the residential structure, the required concrete compressive strength is about 30 MPa for structural works, and it can be possible with high-volume FA as a partial substitute for cement (Hemalatha & Ramaswamy, 2017). Additionally, adding FA and GGBS to RCA increased the concrete compressive strength, modified pore structure, and reduced drying shrinkage than CC (Liu et al., 2023). In the same regard, using different percentages of two fly ash types as replacement of cement proved that can utilization of by-products or wastes usable as cement replacement in concrete leads to more sustainable options and better environmental performance concrete production (Teixeira et al., 2016). Therefore, the selection of FA in this research is due to its role as a by-product waste material for reducing waste generation, keeping resources in use for as long as possible, and maximizing their value. It is considered a sustainable option and perfectly embodies the core principles of CE. In addition, the specific requirements in the residential sector, such as smaller-scale residential projects, enable more experimental investigation of the partial substitution of FA concrete instead of CC (Saldarriaga et al., 2022).

1.3. Circular economy principles for using green concrete

Therefore, applying CE principles with the concepts of regenerative and restorative (Ellen MacArthur Foundation, 2012). Where resources are used for as long as possible to maximize natural resources; furthermore, environmental conservation and economic growth by promoting recycling and reusing waste materials cannot be separated from performance (Schögl et al., 2020). Consequently, the CE strategy presents economic advantages and opportunities. It plays a complementary role in breaking the carbon emissions to enhance the decarbonization of the cement and concrete industries, therefore presenting more interpreting carbon emissions for a sustainable and prosperous future scenario (Favier et al., 2018; Ellen MacArthur Foundation, 2019; Blomsma & Brennan, 2017; Kirchherr et al., 2017). For CE transition in the construction industry must emphasize the structural modifications that recognize causal loops between economic and ecological systems in the usage of concrete and cement materials (Geisendorf & Pietrulla, 2018; Kirchherr et al., 2017; Meyer, 2009). For example, CE strives to divorce

economic development from resource extraction and waste prevention (Ghisellini et al., 2016; Kalmykova et al., 2018; Marsh et al., 2022; Murray et al., 2017). Therefore, operationalizing circularity in the construction process should be cross-disciplinary decision-making from the first project phase (Suchek et al., 2021; Urbinati et al., 2017).

GC has influenced the concrete industry to ensure an optimum carbon footprint scenario that meets the resources and energy efficiency criteria. Consequently, in the selection process of the project's concrete materials, it is necessary to redesign dynamic scenarios of the characteristics of the material value loss and scarcity of natural resources to define suitable alternative materials with the considerations of circularity drivers. Fig. 2 shows the CE hierarchy principles for GC in residential buildings, such as redesign for cement reduction, cost-effectiveness, design for durability, reuse, remanufacturing, and reducing waste at the end of the building life cycle (Gartner & Hirao, 2015; Merli et al., 2018; Nodehi & Mohamad Taghvaei, 2022).

1.3.1. Applied the CE in the early construction process phase

Therefore, 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 (Marey et al., 2022). 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 (Veite & Steinhilper, 2016), (Lederer et al., 2020). Therefore, investigating the causal change cycles between socioeconomic and natural systems should be accounted (Spíšáková et al., 2022), applying more clarification of CE principles to enable the construction and environmental stakeholders to consider a long-term strategy for selecting concrete materials (Kirchherr et al., 2017). Despite the difficulties and obstacles faced by the construction stakeholders for the transitions from a linear economy (LE) CE, such as the massive consumption of concrete materials and the absence of a resources efficiency strategy (Veite & Steinhilper, 2016) using simulation models to transition to CE promote a new opportunity to address the challenges and interventions in the construction industry (Nodehi & Taghvaei, 2022). Therefore, the growing interest in simulation tools facilitates and clarifies the inner relations between the GC materials parameters. The investigation that affects one parameter to another will be applied by identifying the positive and negative relations. Additionally, increasing the cooperation between the project team for materials and information needed leads to appropriate decisions and selection between different concrete types (Nodehi & Taghvaei, 2022; Tazi et al., 2021). To facilitate cross-disciplinary and informed decision-making (Lederer et al., 2020; Linder & Williander, 2017), adopting the GC selection perspective and predicting future scenarios should be investigated to fundamental the operationalization of CE (Geisendorf & Pietrulla, 2018; Spíšáková et al., 2022).

1.4. System dynamics (SD)

In recent decades SD has been allowed to model complex systems in previous research efforts. Several scholars have applied SD to address the complexity of CE transitions by creating models and analyzing complicated variables via computer simulation software to investigate the interconnection of the system variables and their feedback (Jokar & Mokhtar, 2018). Since SD was developed by Jay.W. Forrester in 1950, it is considered a simulation modeling technique that represents the structure of complex systems feedback loops of the materials and information based on stocks, fluxes, and auxiliary variables (Forrester, 1961; Forrester, 2016; Sterman, 2010). Consequently, it helps manage

increased complexity in numerous fields by encouraging closed-loop thinking and comprehending causal structures underlying behavior (Sterman, 2010). However, using SD to investigate the GC can enable proactive system experimentation and give insights into policy and decision outcomes. For example, using SD-based simulations to investigate the trends of CO₂ emission and predict energy consumption in the urban context. (Feng et al., 2013; Fong et al., 2007; Shehryar et al., 2021). Furthermore, in the urban context, using SD for regional planning and natural resources management enables the stakeholder to address complex issues effectively (Ding et al., 2018; Winz et al., 2009), and the integration of environmental assessment and management are investigated by (Kelly et al., 2013) among various modeling approaches. Furthermore, the SD applications (Lauf et al., 2012) are applied to investigate urban development based on the household structure and population.

However, in the concrete and cement industry, the ability of SD to understand and experiment with quantitative and qualitative data for construction projects helps to predict future challenges. Using the SD model for sustainable cement and concrete was investigated as a policy tool (Jokar & Mokhtar, 2018; Nehdi et al., 2004). In the same context, the SD model was used to evaluate several CO₂ emissions policies in the Indian cement industry between (2001–2020) (Anand et al., 2006). In the same scenario, SD was developed to estimate energy consumption and CO₂ emission for the City of Beijing, China, from 2005 to 2030. Furthermore, the cement industry's CO₂ emissions were analyzed by (Ansari & Seifi, 2013) developed an SD model with different scenarios. In the same context, using the SD model to assess the environmental management of the cement industry in the streaming data discussed by (Ekinci et al., 2020; Proaño et al., 2020).

On the other hand, in designing the SD business model for applying CE addressed by (Lewandowski, 2016), the transitions need innovative tools for the decision-makers, who are involved in reducing uncertainties of managing the dynamics and anticipating future scenarios (Pieroni et al., 2019, 2021). Despite the complexity that the construction industry faces for CE, transitions due to linear practices and the massive use of natural resources, there needed to be more empirical studies that cover the gap between the industrial and academic realms.

1.5. Objectives

The primary objective of this study is to identify and analyze the parameters that influence green concrete material selection in the residential building sector through CE principles. The current study investigates several types of concrete to evaluate the selection of GC materials using SD modeling. The model is based on the framework circularity principles to select the most appropriate materials for future residential projects. Therefore, the study aims to:

- Evaluate the environmental impacts of various GC scenarios in residential construction by assessing the resource efficiency, waste generation, and cost-effectiveness of the concrete materials' circularity.
- Investigate and analyze factors influencing the selection of concrete materials at the residential building level.
- Provide insights into the decision-making process for green concrete material selection that aligns with circular economy principles. To achieve that, a framework was proposed for investigating CE transitions, using case study data to create several hypothetical concrete scenarios for investigating the most optimum one compared with the actual scenario, and the study attempts to answer the following:
 - o How can CE principles enhance and support the GC selection for the residential building construction process?
 - o How can several hypothetical concrete scenarios enhance the selection of GC materials using SD modeling?
 - o What parameters influence green concrete material selection through CE in the residential building sector?

1.6. Significance

Therefore, the growing interest in using simulation models to investigate the transitions of CE opens a new opportunity to address the concrete materials challenges and interventions. The current study presents a first attempt to examine the GC circularity principles through the SD simulation model. It provides the first call of action for researchers, construction industry stakeholders, and policymakers to consider using GC materials in Egyptian residential projects by (i) Helping to face the obstacles and challenges for achieving CE by investigating the interaction of inner variables of GC selection to solve the complex system interrelations in the construction process. (ii) Evaluating the impacts of various GC scenarios for implementing the most optimum solutions to help tackle environmental impact and apply resources efficiently. (iii) Promoting overcoming CC challenges and promoting more flexible and sustainable scenarios for the future of residential building projects locally and globally.

2. Material and methods

This research used the SD-Based Framework (SD-BF) to investigate the CE between different GC scenarios through the simulation process. That employs a comprehensive methodology that combines literature review, empirical data collection, system dynamics model, and scenarios analysis. The methods consist of the following phases:

First, Identify the essential parameters for GC materials based on the review of the previous research efforts, which involves an in-depth analysis of existing research and publications related to green concrete, material selection, circular economy principles, and their application in the residential building sector, by focusing on the studies investigated the environmental impact, resource efficiency, and cost-effectiveness.

Second, revise the building drawings by using AutoCAD software and collect data and information based on the project's official documents, such as bill of quantity documents (BOQ) and project timeline, which identifies the initial concrete materials quantities and initial cost; additionally, materials specifications and (Egyptian Standards Specification for Concrete), (Egyptian Building Code) reported (Wagih et al., 2013).

Third, classify five different concrete materials using PCC, RAC, and FA. The selection of the FA and RAC in this study for use in the residential building case study, based on their suitability for achieving CE principles, local availability, improving the model, and the selection of GC materials 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).

Identify the original base Scenario1 (S1) consisting of reinforced Portland cement concrete (PCC- R) applied for all the building's structural and non-reinforced Portland cement concrete (PCC-N) applied for non-structural works, respectively.

Create hypothetical scenarios by using five concrete material types as follows:

Scenario 2 (S2): consists of reinforced Portland cement concrete (PCC- R) applied for structural works and RAC for non-reinforced (RAC-N) applied for non-structural works.

Scenario 3(S3): consists of reinforced Portland cement concrete (PCC- R) applied for structural works and non-reinforced FA (FA-N) for non-structural works.

Scenario 4 (S4): consists of reinforced FA (FA-R) applied for structural works and non-reinforced RAC (RAC-N) applied for non-structural works.

Scenario 5 (S5): consists of reinforced FA (FA-R) applied for structural works and non-reinforced (FA-N) applied for non-structural works

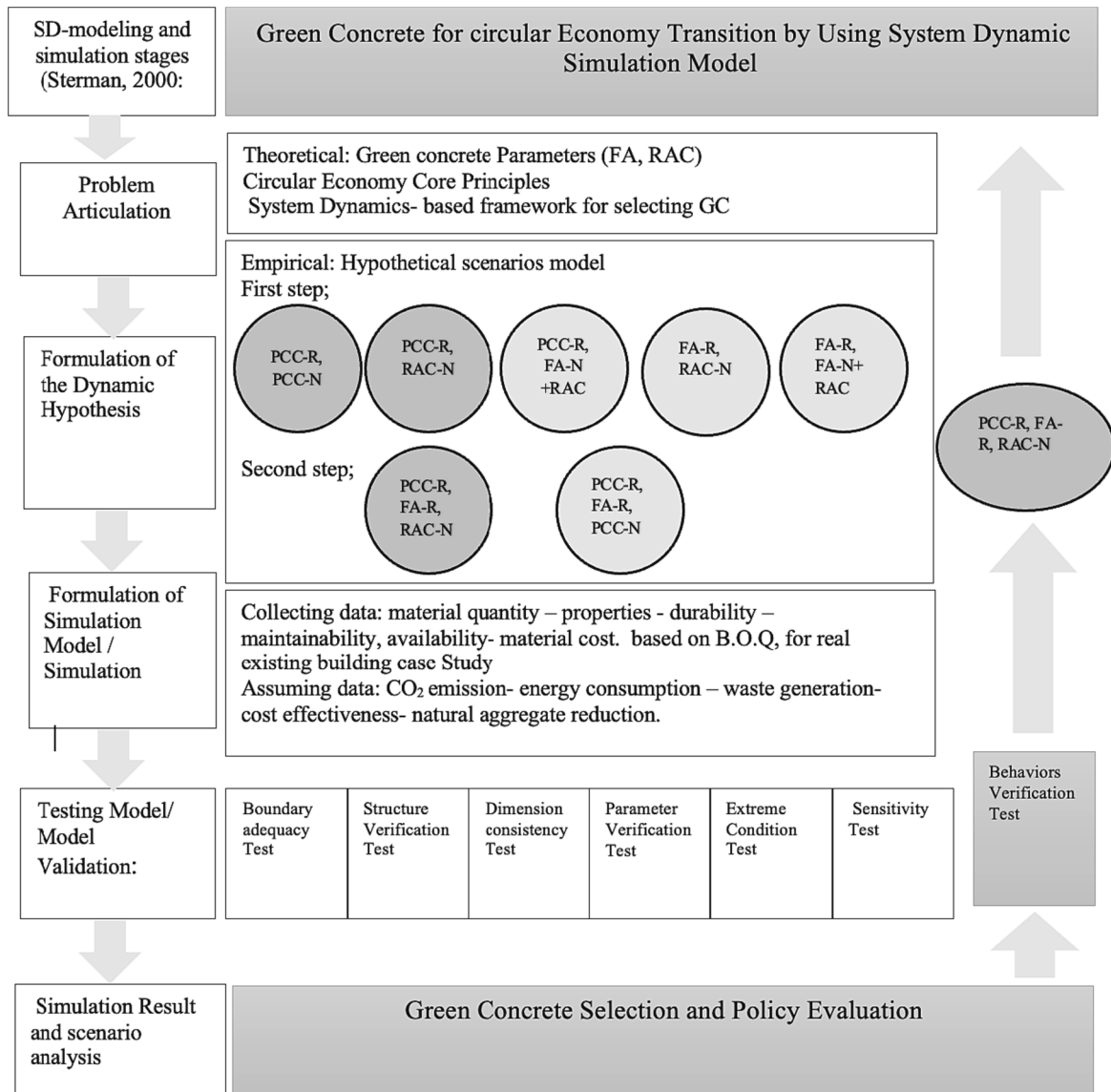


Fig. 3. Research Methodology Structure.

containing RCA materials as replacement of NCA.

Scenario 6(S6): consists of reinforced Portland cement concrete (PCC- R) applied for selected structural parts, reinforced FA concrete (FA-R) applied for selected structural parts, and non-reinforced Portland cement concrete (PCC-N) applied for non-structural works.

Senario7 (S7): consists of reinforced Portland cement concrete (PCC-R) applied for selected structural parts, reinforced F.A. concrete (FA-R) applied for selected structural parts, and non-RAC concrete (RAC-N) applied for non-structural works.

Quantify the seven scenarios to investigate the mix proportions of CC and GC concrete compositions in their corresponding components for (cement, sand, coarse aggregate, recycled aggregate, concrete waste, and cost) circularity principles by using the Absolute Volume Method (AVM), Microsoft Excel, and MS Project software. CO₂ emission was estimated based on the CDIAC's method from cement production reported by (Gilfillan and Marland, 2021; Taylor et al., 2006; Yang et al., 2015; Andrew, 2019). The variety of these scenarios provides more flexibility for the selection process insights into the actual project's concrete selection materials challenges and benefits.

Fourth: Develop a simulation model by using Vensim software to create an SD model, by causal loop diagrams (CLD), and stock and flow (SF) diagrams for causal the interdependencies and feedback loops to

investigate the inner relations among the GC variables that achieve CE based on (Sterman, 2000) five-stage.

Fifth: the most optimum scenarios analysis in term validation and scenario analysis and selecting the most appropriate GC scenario, clarified by building drawing mapping the relation between concrete type and building parts. To present a powerful tool for understanding and managing CE transitions. It can be used to identify the critical drivers of GC, to test different policies and interventions, and to understand the implications of different choices.

However, this methodology focused on using FA and RAC for implementation in a low-rise residential building in Egypt, but it can be applied in different regions and other building typologies, considering the local building regulations, and resource availability, while this methodology encounters application difficulties such as the limited data, local materials availability, lack of developers' and homeowners 'awareness. Furthermore, absence of rules and regulations that encourage using GC, labor skills, and SD technique practices inside the construction industry and concrete market. Fig. 3 shows the structure of SD-BF.

Table 1

Shows the essential green concrete variables based on the review of the circular economy report 2023 and green building rating systems,

GC Variables	Environmental	Economic	Technical	LEED	BREEM	GPRS
Waste management	✓			●	●	●
Reused raw material	✓			●		●
Recycled materials	✓			●	●	●
Durability			✓		●	●
Availability & Locality		✓		●		●
Resource efficiency	✓				●	
Cost effectiveness		✓				●
Carbon emissions	✓			●	●	●
Renewable materials	✓	✓		●		●
Hazard Management	✓			●	●	
Site storage management			✓	●		●
Prefabricated on site			✓			●
Maintainability			✓		●	●
Project cost		✓				●
Embodied Energy	✓				●	
Waste recycled on site			✓			●
Recycled aggregate	✓			●		
Minimize Pollution	✓				●	

3. Results and discussion

3.1. Model development

This section identifies the most critical variables and parameters for GC materials based on reviewing the previous research efforts, rating system, CE report, building code, and concrete code, integrated with the collected data and evaluated from the actual residential project case study. By involves an in-depth analysis of existing research and publications on green concrete for material selection, circular economy principles, and the residential building sector. Furthermore, the conceptual framework of the SD model for CE transitions for GC uses recycled materials selected to investigate the construction industry benefits in the context of cement, natural resource consumption, strength, CO₂ emissions, waste generation, and cost-effectiveness.

3.1.1. The circular economy principles and green concrete variables

We found that using GC materials such as concrete with partial cement replacement by recycled materials, even if industrial waste, by-product waste, and /or CDW, should cover several parameters for achieving circularity. CE's core principles focus on priorities of regenerative resources, stretching the lifespan, and using waste as a resource (Marsh et al., 2022). Using RAC and FA can reduce and improve concrete utilization and prosperities (Golewski, 2018). Based on the CE Report 2023, the core principles will be considered for selecting the GC materials.

Table 1 shows the essential GC variables. The majority of these variables and parameters obtained from intensive literature linked with the most international and local green building rating system parameters, such as Leadership in Energy and Environmental Design (LEED) is the US green building certification program., as well as the Building Research Establishment Environmental Assessment Method, (BREEAM), is a green building certification program developed by the Building Research Establishment (BRE) in the United Kingdom. Moreover, the Green Pyramids Rating System (GPRS) for sustainable building practices in Egypt and the international and Egyptian concrete codes.

Consequently, this finding helps develop the conceptual framework for achieving GC circularity in the next section.

3.1.1.1. The different and constant variables values of GC scenarios. In the case of GC materials, the value depends on the properties and function, which differ from one type to another. The constant and various variables were identified. In this research, constant parameters that couldn't change should be considered in selecting the substitution materials, such as durability, strengthening, and lifespan of PCC. In the same context, we assumed that the unit price of OPC in the construction process is constant in all the concrete scenarios obtained from local materials market prices. Most of the constant variables are estimated based on the requirements of official government residential building regulations such as Egyptian building codes and concrete codes specifications (HBRC. Arabic, 2007). Conversely, various variables, including recyclability, availability, and maintainability, have different reduction rates (natural resources, energy, waste, final concrete cost, and CO₂ emissions). For example, the materials are available in the local markets, and suppliers are obtained from project procurements. In the same context, the GC quantity of the hypothetical scenarios is calculated based on the original scenario in the project's BOQ. The estimation of CO₂ emissions is based on cement production and the inventory of carbon and energy (ICE) (Andrew, R.M. 2019, Bildirici, M.E. 2019, Houghton, R.A.; et al. 2017, Hammond, & Jones, 2008). The data for a concrete cost determined from the annual construction process cost, materials procurement, final construction cost, and the waste percentage and recyclable materials content are calculated and estimated based // on concrete code (Wagih et al., 2013) and revised by third parties, with discussion expert consultants in the construction industry for more accuracy.

3.1.2. The conceptual framework for achieving GC circularity

The conceptual framework was developed based on GC-selected parameters and the CE (10Rs); this framework is considered an initial step and aims to examine the GC circularity through SD modeling five

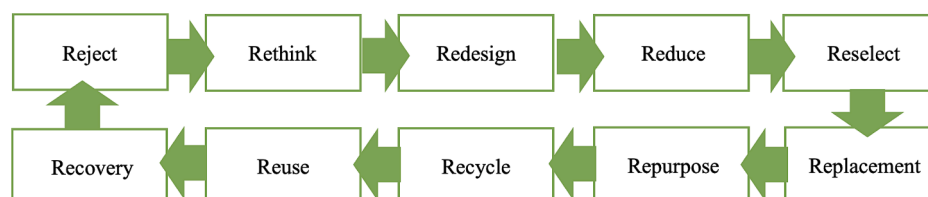


Fig. 4. Conceptual framework of the SD model for CE transitions.

Table 2

The building case study Information.

Description	Area dimension (m)	Floor area (m ²)	Building height (m)
Total land area	29.20 x 21.9	639.48	–
Basement	16.93 x 14.75	249.97	3.35
Ground floor	17.50 x 15.66	274.05	4.00
First floor	17.50 x 15.66	274.05	3.60
Penthouse	8.82 x 14.75	130.10	3.05
Total built area	–	928.17	–
Total building height	–	–	12.00

stages (Sterman, 2000). The framework works through selecting GC materials in the construction of residential building case study during the construction stage. Furthermore, indicates the CE essential considerations for selecting GC and assessing the modeling initiative based on the quantities of the concrete materials in different hypothetical scenarios. As well as the expectation of inputs and outputs exemplifies the optimum feedback between the process stages.

The framework helps as an essential tool for investigating GC materials' circularity and starts with rejecting conventional materials, rethinking for new and innovative solutions, redesigning for the most reducing consumption scenario, then reselecting and replacing for the reusing and recycling purposes, and finally, recovery and redesigning new policy. Fig. 4 shows the framework of CE transitions for selecting suitable GC materials based on natural resource efficiency, cost-effectiveness, and environmental impact in the construction of residential building projects.

3.2. Case study

3.2.1. Building data and information

The chosen project is a new residential building in New Cairo City, Egypt. The total land area is 639.48 m², and the floor area is 928.17 m². The building has a basement, ground floor, first floor, and penthouse, which are considered the common building typology that follows the government development strategy described in Table 2. The construction process was estimated to take over 30 months, and the building's structural system is reinforced concrete (RC). Fig. A2 illustrates the details of the building drawing and floor plan. The data were collected from the building consultant and official government documents with site observation and discussion with the project team and consultant experts.

3.2.2. Classification of concrete materials

In the current research, FA and RAC, in addition to PCC, are utilized through several concrete scenarios for the construction process based on their suitability and local availability (Saha, 2018; Golewski, 2018; Marvila et al., 2022). We classified the hypothetical different GC materials scenarios based on CC's original scenario S1. We started with categorizing the original scenario S1 followed by other scenarios, S2, S3, S4, S5, S6, and S7. We identified the concrete function (FA-R & PCC-R) used for reinforced concrete and (PCC-N, RAC, and FA + RAC) for non-reinforced. Then, each scenario quantity is calculated, considering the total concrete quantity is 482.16 m³, which is a constant value in all scenarios. Table 3 shows the concrete types and scenarios classification in the context of concrete code specification and components. Fig. 5 shows the variety of concrete types, such as C1 (PCC-R), C2 (PCC-N), C3 (RAC-N), C4 (FA-R), and C5(FA-N) used in scenarios provide more valuable insight through the simulation process, allowing more circularity and resource efficiency based on the CE core principles.

S1, S2, and S7 were selected as examples for SD modeling and simulation to highly investigate CE principles and provide holistic insights into the construction process timeline for using recyclable materials, reducing, and reused, which led to more clarification of using GC

Table 3
classified the quantity of concrete types and concrete scenarios.

Assessed the quantity of concrete types and concrete scenarios:															
Scenarios/Concrete 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		
	C1	C2	C1	C3	C1	C5	C4	C3	C4	C5	C1	C4	C2	C1	C3
Concrete quantity/m ³	320	162.2	320	162.2	320	162.2	320	162.2	320	162.2	190	130	162.2	190	130
Strength	35 N	20 N	35 N	16 N	30 N	20 N	30 N	16 N	30 N	20 N	35 N	30 N	20 N	35 N	30 N
Cement: sand: aggregate	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	0.3:0.7:1:2	1:1:2	0.3:0.7:1:2	1:2:4	1:1:2	0.3:0.7:1:2

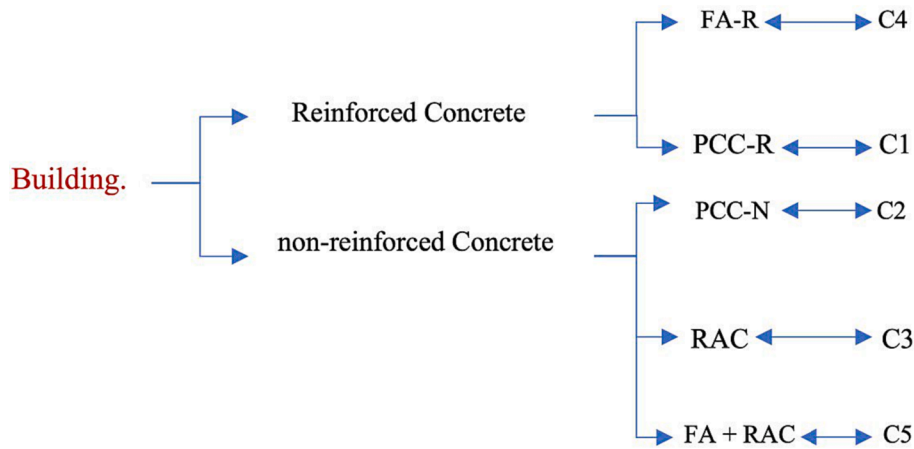


Fig. 5. Concrete materials and classification used for different scenarios.

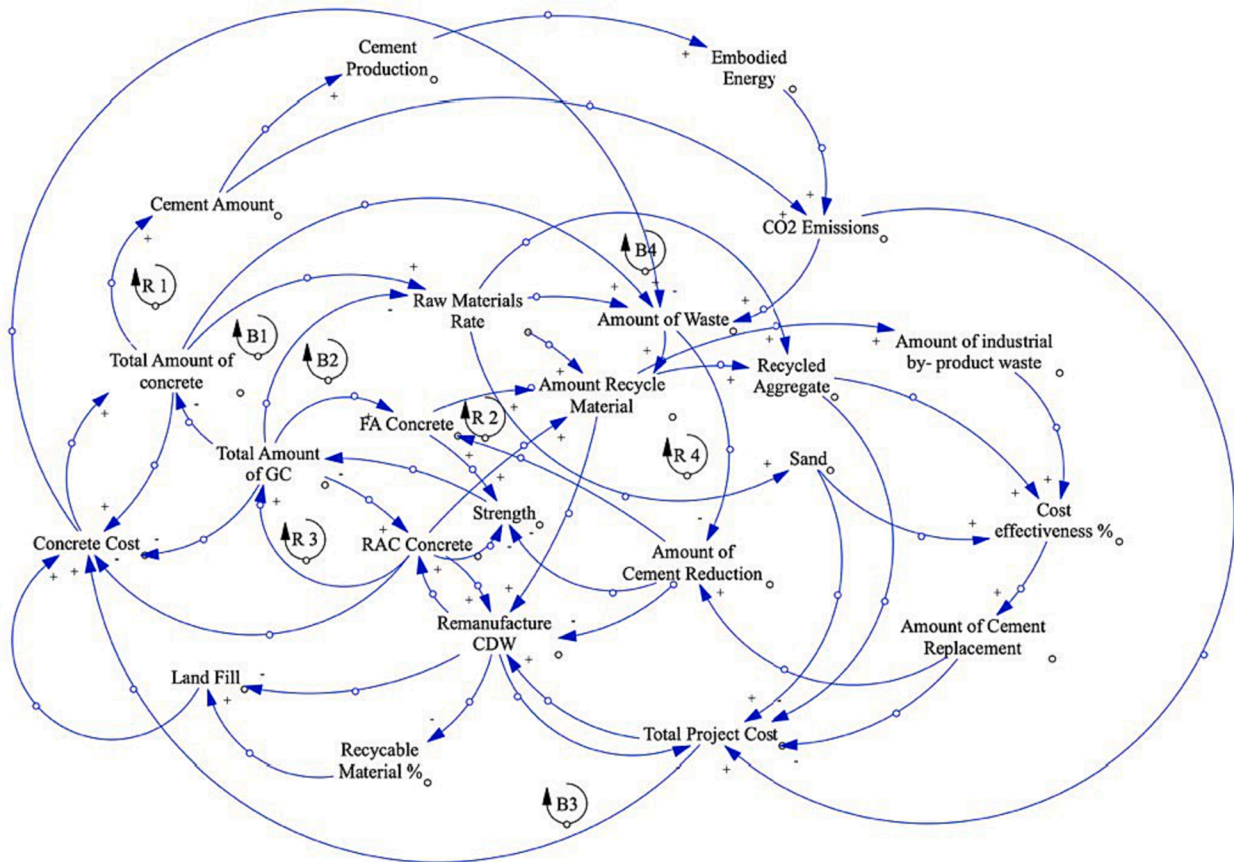


Fig. 6. The green concrete Casual loop diagrams CLD for Circular Economy transition (authors).

for the residential building sector.

3.3. Modeling of the GC parameters

In this section, the SD is considered as a tool to investigate the positive and negative inner relations between the parameters that enhance the GC materials selection for achieving CE (Guzzo et al., 2022). We create dynamic models with various levels and details. Vensim simulation software anticipated the model performance over time. In this context, the SD approach estimates the changes and inner relations in the systems between different scenarios.

3.3.1. The causal loop diagram

In the current research, we created a causal loop diagram CLD to depict the primary feedback and demonstrate the structure of the SD model. It clarified how the interactions of all variables dynamically influence the system and how feedback loops are determined through the model dynamics. We started with the qualitative discovery of the feedback loops that describe the dynamic behavior of different GC scenarios and Fig. 6. Illustrates the individual and group casual links for achieving CE during the construction phase of a residential building. The CLD variables were selected based on the essential GC parameters, shown in Table 1, after being modified to suit the building case study data and

Table 4
Description of variables in 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	%
1TARCM	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	2,117,105	LE
TCCM	Total concrete cost monthly	70,570.2	LE
UCOPCM	Unit cost OPC monthly	15,123	LE
COPC	Cost OPC	453,691.3	LE
TARCC	Total amount reduction cement cost	136,956.0	LE
VROPCCS1	Value reduction OPC cost S1	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
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 fly 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 %	%
TCO2	Total CO ₂ emission reduction	34.9	ton
CO2M	CO ₂ emission monthly	5.9	ton

type to allow more opportunities for change and argue future policies in future construction projects. We found positive feedback loops in [R1- R2 -R3, R4], where the variables in the loops will eventually positively affect themselves, and the change in one variable changes in another variable in the same direction. For instance, in a positive feedback loop R1, increasing the amount of CC will increase project cement consumption and production, increasing embodied energy and thereby increasing CO₂ emissions and the concrete cost. Consequently, this increases the total project cost and the total amount of CC consumption.

In the positive feedback loop R4, A significant increase in the amount of waste indicates a decrease in the cement reduction strategy, a decrease in the remanufacture strategy in CDW, and a decrease in the total recyclable materials % rate. This increases the total amount of disposal to the landfill and increases concrete costs, then 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 and apply the same context of the feedback loops R2 & R3. On the other side, we found negative feedback loops in the loops, for example [B1- B2- B3,B4] and described as the following; we notice that the negative loop is B1 shows the changes in variables within the causal loop that negatively affect the opposite direction. Since the consumption of the total amount of concrete will increase, the consumption rate of the raw materials leads to an additional amount of waste, which increases the opportunities for the number of recycled materials. Consequently, increase the CDW remanufacture strategy, then additional RAC materials added, which increases the total amount of GC, then diminution the total amount of CC. Finally, the extra CC reduction leads to using more GC in the project, and the B2 loop works in the same context. B2, an increase the GC usage will reduce the raw materials rate consumption, and increase the recycle aggregate, then decrease total project cost and increase the chance of remanufacturing CDW as an RAC, which is lower in strength, which leads to a reduction in the GC usage in the future project.

In the B3 loop, increases in the total project cost led to an increase in concrete cost and its consumption amount and an increase in the amount of recycled materials and recycled aggregate, then decreased the total project cost. Whereas we found in the B4 loop a significant amount of waste decreases in the cement reduction strategy, decreasing the CDW remanufacture strategy will decrease total recyclable materials rate. Thereby increasing the total amount of waste disposed to the landfill, which reflects on increasing the concrete cost, then decreasing the total amount of concrete, and finally decreasing the amount of waste. Therefore, clarifying the model's underlying assumptions is crucial before moving on to the GC- SF diagram to improve its robustness and applicability. For CE transition, the model's behavior variables met the core principles' needs, and each GC scenario's effects were analyzed and handled in the context of the same purposes.

3.3.2. The stock and flow diagram (SF)

However, the SF diagram identified relationships between the various system components, considered a central idea in dynamic theory (Stermann, 2000) due to its ability to map the stocks and flows networks using conceptual and mathematical definitions. The SF diagram was created based on the CLD by using Vensim software to identify the circularity between various concrete materials' parameters during the thirty months of the construction process. First, define the model boundary and key variables that affect GC selection for achieving CE. The description of the most significant variables in the SF diagram is listed in Table 4.

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. Table 4 The description of each identified parameter. Then, these flow rates and stock combinations by simulating the SD mode are shown in Fig. 7. The typical structure of the SF diagrams notation is followed, as shown in Fig. A1 in the Appendix (Stermann, 2000).

3.4. Model validation

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

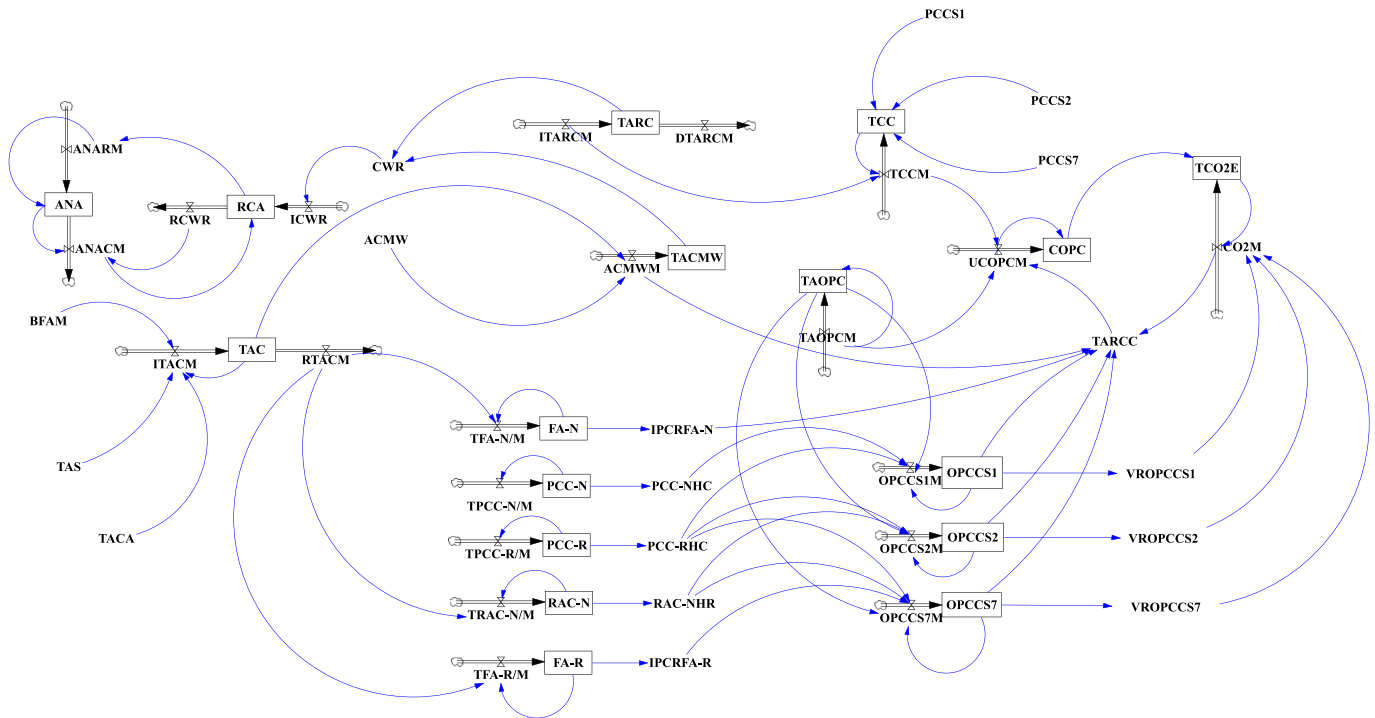


Fig. 7. Stock Flow diagram (SF).

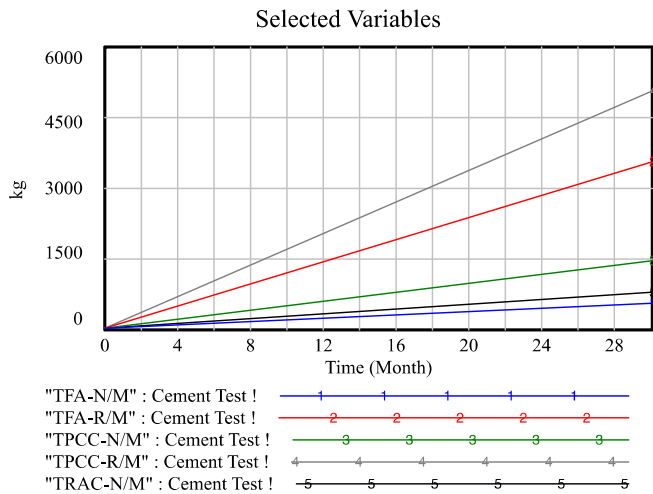


Fig. 8. The Cement consumption in different concrete types.

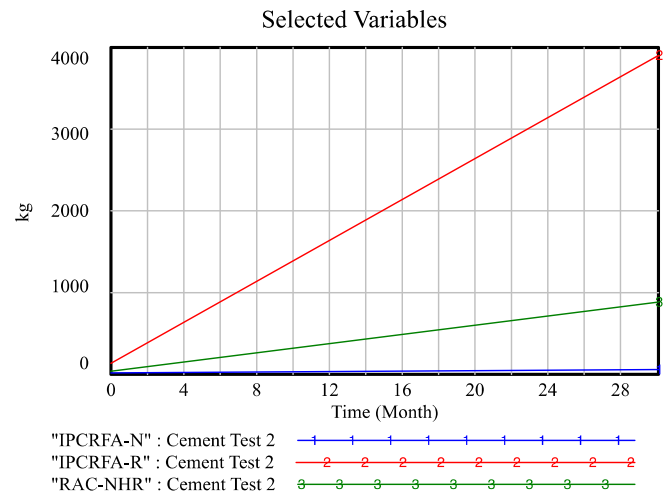


Fig. 9. Cement replacement by industrial waste and recycled aggregate consumption.

parameters and equations in the proposed SD model. The developed model provided input values for specific parameters to run the simulation. This ensures that the model accurately represents the actual environment before running the simulation (Richardson and Pugh, 1981; Senge, 1990).

4. Simulation results

4.1. Simulation analysis of GC circularity

The simulation process for using GC for achieving CE during the construction phase of the residential building was applied after identifying parameters that needed values input to run the simulation, as shown in Table 4 in the previous section. The simulation results investigated the cement, natural aggregate, CO₂ emissions, waste reduction rate, and concrete cost for building case study structural and non-

structural works during the thirty months based on the project timeline for the construction phase.

4.1.1. The cement consumption for different concrete types scenarios

The simulation results of cement consumption in different concrete types are 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. Fig. 8 illustrates test 1, the simulation result of the amount of cement consumption in different concrete types used in S2 and S7.

Cement test 2: examined the industrial waste as FA and RAC for cement replacement. We noticed in Fig. 9 that the variables such as industrial product cement replacement FA-reinforced per month

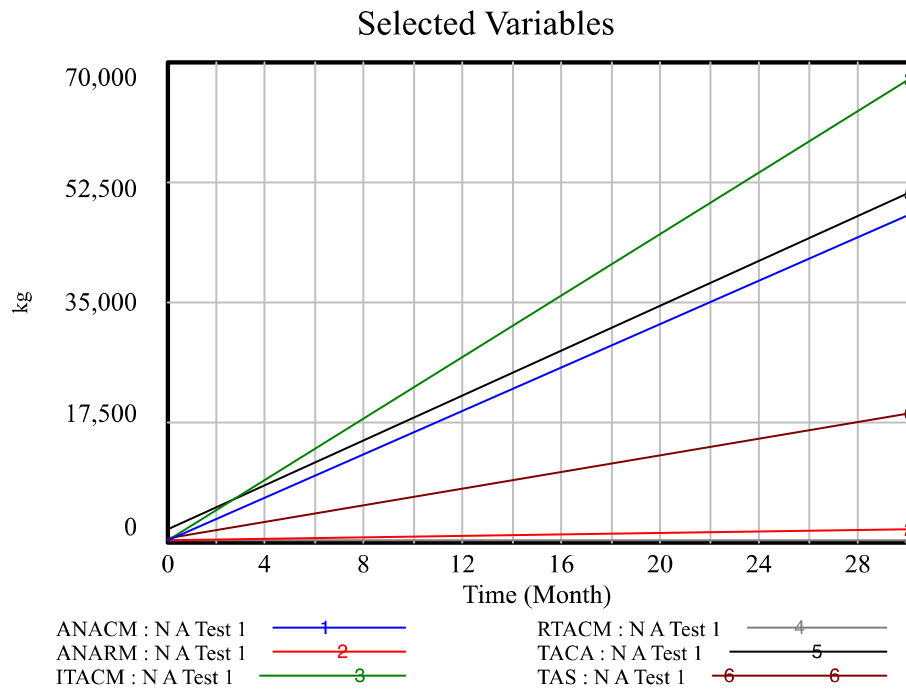


Fig. 10. The simulation result of Natural aggregate and concrete consumption and reduction of monthly.

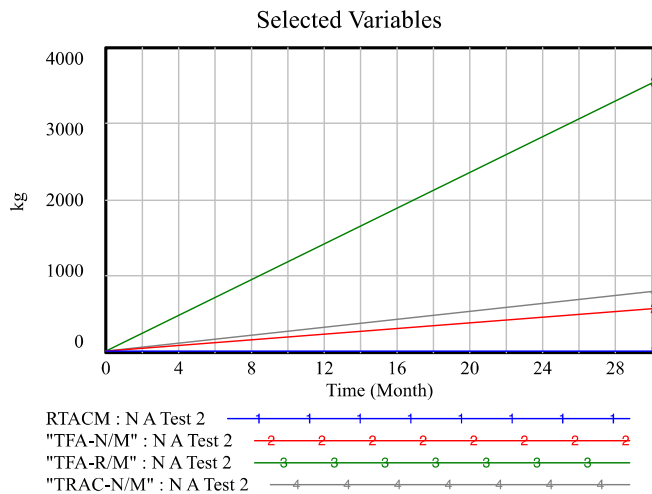


Fig. 11. Simulation results for monthly use of recycled materials in three green concrete types.

(IPCFA-R/M) is higher than recycled aggregate concrete- non-reinforced high recyclable (RAC-NHR), and industrial product cement replacement fly ash- nonreinforced (IPCFA-N) has no consumption, due to its usage limitation.

4.1.2. The natural aggregate (NA) and recyclable materials

Test 1 shows the simulation result of the relation between the total amount of natural aggregate consumption monthly (ANACM), and the amount of natural aggregate reduction monthly (ANARM) after applying the reduction strategy and using RA. Furthermore, 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). Fig. 10 illustrates the natural aggregate test1.

Test 2: It can be seen in Fig. 11 the relation between concrete types with recyclable materials FA-R monthly (TFA-R/M) is the most concrete

type that has a recyclable materials quantity, followed by the total amount of RAC non-reinforced monthly (TRAC-N/M), and the total amount of FA non-reinforced monthly (TFA-N/M), without no effect for reduction total concrete consumption, (RTACM), because it considered as a constant variable.

4.1.3. The CO₂ emissions in different concrete types

We estimated the CO₂ emission based on the calculation using CDIA's method for the cement production OPC type, that one ton of cement produced $0.136 \times 3.667 = 0.50$ tons of CO₂ reported by (Andrew, 2019; Yang et al., 2015; Marey et al., 2022). The simulation illustrates the highest CO₂ emissions monthly for different concrete types; 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 OPC quantity of concrete S1, that considered as highly CO₂ producer as referred by CO2M shown in Fig. 12.

4.1.4. The construction waste reduction in different concrete types

It is noticed in Fig. 13 that the relation between the total amount rate of concrete materials waste monthly (ACMWWM) increases the concrete waste recycling (ICWR) rate and reduce the concrete waste recycling (RCWR) rate. Furthermore, it clarifies the relation between the rates of decreased and increased total amount of reduction cement monthly (DTARCM) and the total amount of reduction cement monthly (ITARCM) over time. This indicates the overall amount of project concrete waste reduction is still marginal and shows a lack of applied circularity and poor implementation of waste regulations in residential projects. Consequently, the fundamental solution for waste reduction is to apply on-site sustainable waste management by improving the waste regulations to increase recycling, remanufacturing, and reusing of concrete waste, thereby reducing waste generation and eliminating the illegal CDW dumping for roadside and landfill; this was supported by (Ismail, et al., 2023; Daoud, et al., 2023).

4.1.5. The cost-effectiveness of different concrete types

The relation of the three scenarios concrete cost identified depends on the cement and supplementary materials, natural aggregate, and recycled aggregate. In this research, the cost is limited to OPC cost and

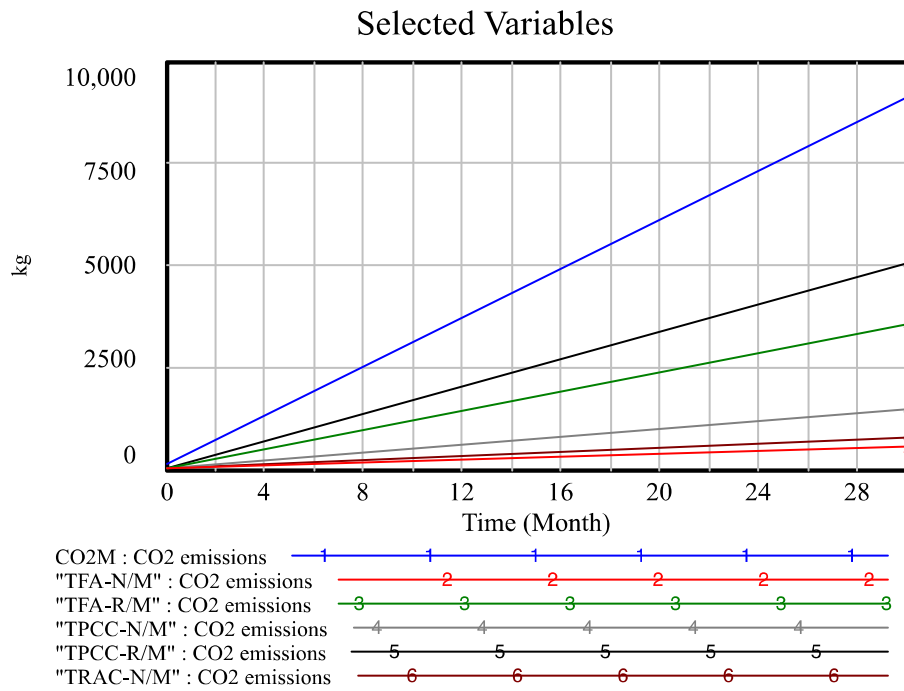


Fig. 12. Simulation results for CO₂ emissions.

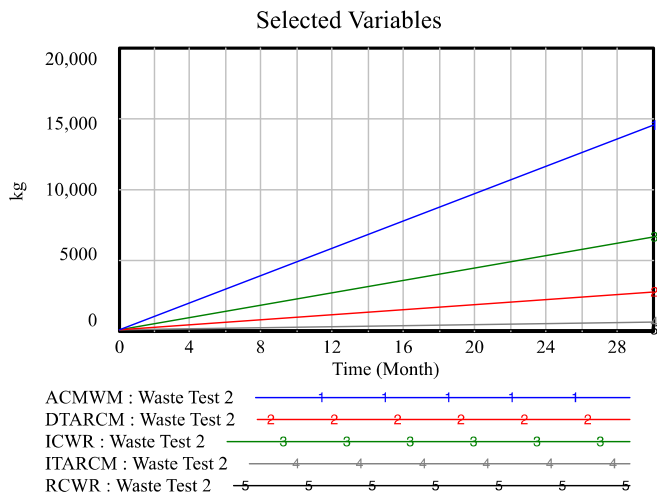


Fig. 13. Simulation results for the increase and the decrease of concrete waste.

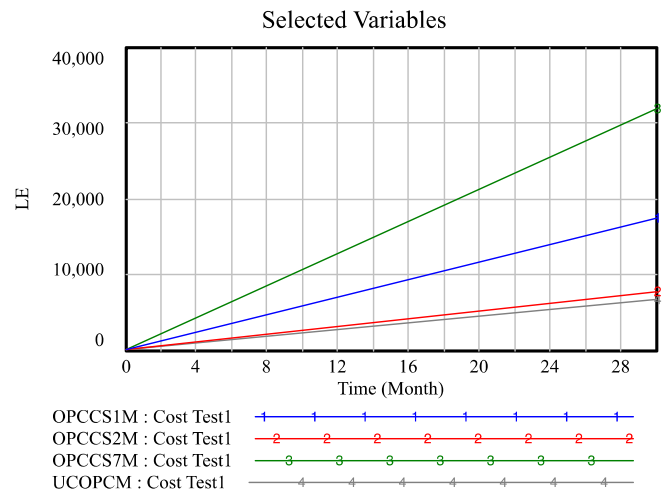


Fig. 14. The amount of OPC cost for S1, S2, and S7.

supplementary cementitious materials such as FA and RAC for several aspects. The cement cost of S7 increases by 76 % compared with the cement cost of S1, and the cement cost of S2 is the lowest price, which decreases the total cost by 16.6 %. the simulation as shown in Fig. 14 shows that the relation between the cement cost of scenarios is OPCCS7M > OPCCS1M > OPCCS2M.

5. Concrete scenarios analysis

5.1. The effects of using GC for achieving CE

This study aims to identify and analyze the parameters that affect green concrete material selection in the context of circular economy principles. To investigate and analyze the previous scenarios for selecting the most optimum CE that can be achieved in the construction of residential buildings, we start with an analysis of the SI as a scenario base and the other six hypothetical scenarios. The simulation result

showed how different scenarios could influence the CE principles, such as cement consumption, natural aggregate, waste reduction, CO₂ emissions reduction, and material cost. Table 5. shows the benefits of different concrete scenarios and highlights the three selected scenarios.

Table 5. identified the total concrete quantity for the building case study drawing and dimension-based on the reference data collected from project documents B.O.Q, using AVM, after revising the original building drawing by Autocade were used for quantifying the hypothetical scenarios, as well as the classifications for each scenario considering the (Egyptian Standards Specification for Concrete), (Egyptian Building Code), and the local government regulations for the residential building in Egypt as mentioned in section 2. The result showed the percentage of OPC in CC, RAC, and FA concrete with seven scenarios. the cement reduction reached 19.8 % and 11.4 % in the most optimum scenarios, as a follow, started with full ratio cement consumption of 100 % in the CC as a S1, followed by 89.6 %, 86 %, 66.37, 62.75, 90.55 %, and 80.19 % for S2, S3, S4, S5, S6, to S7 respectively. The total amount of cement per

Table 5
The benefits of using GC circularity in cement reduction, CO2 emissions, Natural aggregate, waste reduction, and cost-effectiveness.

Concrete quantity	Scenario 1			Scenario 2			Scenario 3			Scenario 4			Scenario 5			Scenario 6			Scenario 7		
	PCC-R	PCC-N	RAC-N	PCC-R	PCC-N	RAC-N	PCC-R	PCC-N	RAC-N	FA-R	FA-N	RAC-N	FA-R	FA-N	RAC-N	PCC-R	FA-R	PCC-N	PCC-R	FA-R	RAC-N
Concrete component ratio	1:1:2	1:2:4	1:4:8	1:1:2	1:4:8	1:4:8	1:1:2	1:4:8	1:4:8	0.3:0.7:1:2	0.3:0.7:4:8	0.3:0.7:1:2	0.3:0.7:1:2	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
The amount of cement /ton	174.2	50.4	27.2	174.2	50.4	27.2	174.2	50.4	27.2	121.9	19	121.9	121.9	19	121.9	103.4	49.5	50.4	103.4	49.5	27.2
Cement/ ton	224.6	201.4	149.1	193.2	201.4	149.1	193.2	201.4	149.1	149.1	19	140.9	140.9	19	140.9	203.3	49.5	50.4	180.1	49.5	27.2
Cement/ bag	4,492	4,026.6	2,981.5	3,863.6	4,026.6	2,981.5	3,863.6	4,026.6	2,981.5	2,981.5	19	2,818.6	2,818.6	19	2,818.6	4,067.5	49.5	50.4	3,602	49.5	27.2
Cement %	100 %	89.6 %	66.37 %	86 %	89.6 %	66.37 %	86 %	89.6 %	66.37 %	66.37 %	117	66.37 %	66.37 %	117	66.37 %	90.55 %	81 %	81 %	80.19 %	81 %	27.2
t CO ₂	176.3	158	118	151.7	158	118	151.7	158	118	117	118	110.6	110.6	118	110.6	159.7	154	219	141.4	154	118
Sand /ton	378	219	118	378	219	118	378	219	118	378	118	378	378	118	378	597.4	154	219	224.4	154	118
Sand / ton	597	496	496	496	496	496	496	496	496	496	496	496	496	496	496	597.4	154	219	496.8	154	118
Sand %	100 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	83.1 %	100 %	81 %	81 %	83.1 %	81 %	118
Aggregate/ton	658.3	381.2	185	658.4	381.2	185	658.4	381.2	185	658.4	205.3	658.4	658.4	205.3	658.4	391	268	381.3	391	268	185
NCA/ ton	1039.5	843.4	843.4	843.4	843.4	843.4	843.4	843.4	843.4	843.4	205.3	843.7	843.7	205.3	843.7	1040.3	268	381.3	844	268	185
NCA %	100 %	81 %	81 %	83 %	81 %	81 %	83 %	81 %	81 %	81 %	81 %	83 %	83 %	81 %	83 %	100 %	81 %	81 %	81 %	81 %	185
Cement Cost/LE	351,826	101,865	54,857	351,826	101,865	54,857	351,826	101,865	54,857	1,028,872	274,664	1,028,872	1,028,872	274,664	1,028,872	208,896	715,633	101,865	208,896	715,633	54,857
	453,691	406,683	626,490	406,683	406,683	626,490	406,683	406,683	626,490	1,083,729	274,664	1,083,729	1,303,536	274,664	1,303,536	1,026,394	715,633	101,865	979,386	715,633	54,857

ton and the number of bags used to estimate the cost. 6 %, 66.37, 62.75, 90.55 %, and 80.19 %, respectively. On the other side, the reduction of NA started after using recycled materials as a substitution material for cementitious materials, reaching 19.1 % reduction, whereas the lowest consumption level of 81 % in S2, S4, and S7 to reach 842.1 tons, followed by 83 % in S3, and S5 with amount 863.7 tons compared with the S1, and S6 which consumed 100 % of the NCA in S1. This variety of results adds more evidence for controlling the consumption of cement and NA, and there is a high ability for applying GC circularity in the residential sector. Providing insights into concrete selection materials to investigate the reduction, reuse, and recyclability of the total quantity of concrete components.

5.2. The circularity performance of the optimum scenarios

The circularity performance of the optimum scenarios for GC helps reduce the construction sector's environmental impact. The 10R circular economy principles are used to guide GC selection and achieve CE in the construction process of residential buildings. Fig. 15 illustrates the 10Rs CE principles of the five concrete types used in optimum scenarios. These principles can guide the use of GC in the construction process of residential building projects. These principles started with rejecting the CC and natural resource consumption and refusing the use of materials and products that harm the environment. This opens opportunities for redesign and rethinking of innovative GC materials (Marey et al., 2022). The selection of these materials can reduce negative environmental impact and achieve circularity performance. Their substituting process can be applied easily with the same strength, functionality, and durability as the CC (Nodehi & Mohamad Taghvaei, 2022). Additionally, the replacement and repurposing play several crucial roles in recycling and reusing waste as new material sources, such as RAC and FA (Saha, 2018; Golewski, 2018. Marvila et al., 2022). Aiming to redesign the regulations for new policies that enhance and recover the natural resources and waste generation during the concrete material's life cycle.

6. Conclusion

This study investigated the selection of GC materials to reduce the environmental and economic impacts of increasing residential buildings' concrete materials consumption, emphasizing the role of GC in achieving a CE. Using SD modeling to assess circularity performance based on real construction data. Vensim software generates CLD and SF diagrams, revealing interrelationships in optimal GC scenarios. The SD-BF method was used to assess the circularity performance of the optimum scenarios, which aligned with CE principles. It uses SD to quantify the performance of various scenarios in reducing cement, aggregate, CO2 emissions, cost, and waste during construction, potentially benefiting real residential applications. The simulation model helps the construction stakeholders identify the proper GC type and scenario that can contribute to CE maximum benefits and reduce the CC's negative impacts for the residential building projects in the future by:

- Present a conceptual framework to investigate and analyze the factors influencing the selection of GC materials in the context of the residential building type.
- Using FA, RAC, and PCC to classify and compare several hypothetical GC scenarios with the actual scenario of reinforced and non-reinforced concrete for the structural and non-structural building parts improves closing the concrete materials loop.
- Propose an SD model based on the CE core principles to quantify and simulate the GC scenarios' performance of reducing cement, natural aggregate, CO₂ emission, cost, and waste during the case study's construction phase.
- Offer the CLD and SF diagrams to identify the interrelationships between the GC circularity variables of the most optimum scenarios.

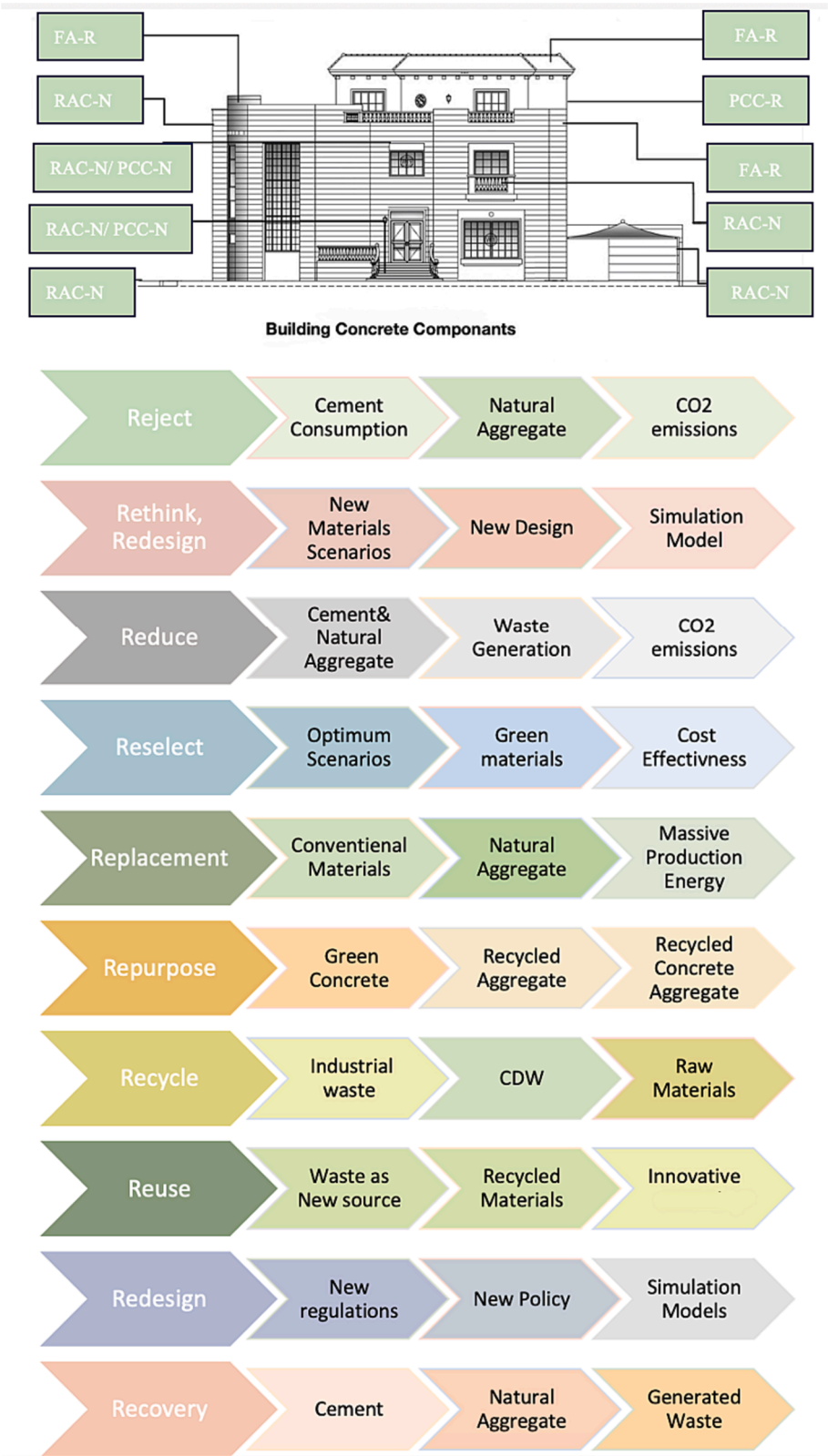


Fig. 15. The 10Rs CE principles for using of GC in the construction process of residential building.

- Improve the GC selection through the simulation model by analyzing the effects of changing several scenarios.
- Provide insights into the decision-making process using dynamic conditions for the selections that align GC materials variables and CE principles.

Presenting an SD model has the potential to be used for GC selection in real-case study residential applications, which can provide various benefits for time and cost from the early stage. The study explored adopting GC materials selection in residential projects to achieve CE by partially CC substituting with FA and RAC with equivalent strength,

functionality, and durability using an SD model. While the current SD model is limited to residential cases, it can adapt to other construction projects. Finally, selecting GC for CE requires more comprehensive data and collaboration among stakeholders for expanding GC materials usage for local, regional, and global levels. As a result, the study recommends further research using various GC materials for other building typologies at the construction and design phases to simulate environmental performance for future construction projects.

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CRediT authorship contribution statement

Heba Marey: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Investigation, Resources, Writing –

original draft, Writing – review & editing. **Gábor Kozma:** Conceptualization, Validation, Investigation, Resources, Supervision, Writing – review & editing. **György Szabó:** Conceptualization, Formal analysis, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data produced and processed in this study are included in the published article. In addition, datasets can be acquired from the corresponding author for appropriate purposes.

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Appendix

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.

Fig. A1. Stock and Flow Diagram notations(Sterman, 2010)



Fig. A2. The front and rear elevation on the left and the ground and first floorplan drawing on the right.

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