Abstract: Cement is the key ingredient in concrete, which is the most consumed resource on the planet after water. As an energy-intensive industry, cement production is one of the largest sources of greenhouse emissions in the world today. The demand for cement is synonymous with the growth in infrastructure demand and per-capita gross domestic product in the world, calling the need for mitigation measures within the industry in order to contribute to the global climate change efforts. System dynamics (SD) is a simulation approach that is used for studying the nonlinear behaviours in complex systems over time, often used in industrial domains for emission forecasts as well as policy experimentation. With the adoption rates of mitigation strategies in the cement industry being inadequate, there is a need for improvisation in policymaking through better decision-support tools. In this paper, a comparative overview of the studies that specifically utilise the SD approach for evaluation of carbon mitigation strategies in the cement industry is presented on the basis of their scope, model description, scenarios tested, and featured mitigation methods. Additionally, the potential for improvements in future studies is discussed.

Keywords: carbon mitigation; cement industry; sustainable energy use; energy and environmental policy; system dynamics; decision support; policy evaluation; management; industrial emissions; green innovation

1. Introduction

Cement is a major component of building materials, such as mortar and concrete, consequently making it one of the most important resources for the developing world. In 2018, 4.1 gigatons (Gt) of cement was produced in the world, with a forecasted production set to cross 5 Gt by 2045. Producing cement is an energy-intensive process, which also releases a large amount of carbon dioxide (CO₂) as a by-product. As per the efficiency trends in 2012, an average cement plant generates a ton of atmospheric CO₂ for every ton of cement produced [1]. According to a report by the Intergovernmental Panel on Climate Change (IPCC), the cement industry accounted for 7% of the global anthropogenic CO₂ emissions in 2005 [2]. Given the scale of emissions from the cement industry and its contribution to climate change, it has become one of the focus industries for emission reductions in conventions such as the Paris Agreement under the United Nations Framework Convention on Climate Change [3]. The Cement Action Plan of the Low Carbon Technology Partnerships initiative by the World Business Council for Sustainable Development (WBCSD), which encompasses several major cement producers, accounting for 30% of the global production, has been exploring various policy frameworks to reach its goal of a 20–25% reduction in emissions by 2030 [4]. Within the cement production process, about 50% of emissions are generated through the process of calcination in the preparation of clinker, which is the main constituent of cement. The remainder of the emissions are generated through the use of carbon fuels and electricity consumption [5]. Depending on the individual parameters of
each cement plant and region, there is a huge potential for carbon mitigation in the cement industry through methods such as waste heat recovery (WHR), carbon capture, low carbon intensive fuels, and blended cements. Given the capital-intensive nature of these methods, the existing policies have not been very effective in propelling the cement industries to adopt the aforementioned mitigation methods. However, through improved evaluation tools, it is possible to design balanced policies that would enable the implementation of mitigation strategies that are economically feasible. The International Finance Corporation has estimated the WHR power capacity within the existing cement industry to be between 1.6 and 2.9 gigawatt electrical (GWe) in 2013. Without any significant policy interventions, the cement demand is expected to grow at a moderate rate until 2030, prompting a similar growth in the cement industry and a mitigation potential.

Depending on the specific objectives, the mitigation policies and their consequent carbon emissions are often evaluated through a variety of simulation techniques, including Monte Carlo [6,7], multi-agent-based simulation [8,9], discrete event simulation [10], and system dynamics [11]. Among the methods specified, system dynamics (SD) is a holistic, non-discrete type of simulation technique that is gaining precedence in the domain of carbon policy evaluation because of its ability to handle complex intricacies of socio-economic factors when analysing and estimating trends such as cement demand [12]. The primary objective of the paper is to present a comparative overview of studies that specifically utilise SD models for evaluation of one or more carbon mitigation strategies by estimating the carbon emissions under different socio-economic policy scenarios applicable to the cement industry. This paper thereby emphasises the specific goals of each chosen study and their featured feedback sub-systems for the purpose of exploring the research gaps in the domain.

In order to provide contextual insights into the topic, the concept of SD is briefly described in Section 2, with an elucidation of the popular carbon mitigation techniques currently employed within the cement industry later in Section 4. Additionally, the current implementation rates of these mitigation techniques are presented to highlight the need for further attention on this topic in Section 5. Section 3 states the methodology followed for sourcing the literature later reviewed in Section 6. The gaps in the current application of SD for mitigation evaluation are identified in Section 7, followed by the conclusion and recommendation for the direction of future studies when applying SD modelling for evaluating the carbon mitigation strategies in the cement industry.

2. System Dynamics (SD)

SD is a simulation technique that is being actively utilised in decision making, policy planning, and evaluations across a range of industrial domains, including carbon mitigation. Figure 1 shows the number of articles published since 2000 with the combination of keywords “system dynamics” and “policy”.

SD is a holistic, non-discrete type of simulation modelling that typically employs “an interlocking set of differential and algebraic equations developed from relevant experiential data” [13]. The approach extensively utilises cause-and-effect relationships and feedback systems, which help in the identification of complex behavioural patterns over time, thereby enabling the study of long-term unanticipated consequences and policy resistances. SD facilitates both qualitative and quantitative approaches to problem solving, allowing for the utilisation of written and numerical data in combination with mental models to gain deeper insights into the underlying structures and feedback linkages responsible for the behaviour of the system. By aggregating the available data into different levels of detail, the approach allows for the uncovering of different aspects of the system that could be relevant to different stakeholders of the system. Active participation of the stakeholders in the model-building process allows for determination of the intended rationality associated with business decision making [14].
Causal loop diagrams (CLDs) and stock-and-flow diagrams are typically used for the visual representation of SD models. A CLD allows for dynamically describing complex systems through the use of varying combinations of positive reinforcing loops, acting as a self-reinforcing mechanism, and negative balancing loops, which act as a corrective, goal-seeking mechanism [15]. Figure 2 is an example we have prepared to demonstrate the concept of causality, with (a) showing a reinforcing loop in which the demand for new infrastructure leads to higher cement production, which, in turn, results in a higher availability of cement in the region, further stimulating the demand for new infrastructure; and (b) showing a balancing loop in which the increase in carbon emissions leads to a higher emphasis on mitigation measures, which, in turn, leads to a reduction in emissions.

Figure 2. Example illustrations of causal loop diagrams (CLDs), with (a) a positive reinforcing loop; (b) a negative balancing loop.

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Figure 1. Number of documents published under the combination of keywords “system dynamics” and “policy” between the years 2000 and 2020, as retrieved from Scopus-indexed publications.
“Cement sales” as flows, which refer to the transactions changing the value of the stock. The flows, “Cement production” and “Cement sales”, are influenced by both current stock of cement available and as well as the external demand. The variable “Cement demand” is influenced by the current stock of cement available as well as inputs originating outside of the system boundary.

![Stock-and-flow diagram](image)

**Figure 3.** Example illustration of a simple system dynamics (SD) model represented in a stock-and-flow diagram.

The SD approach is generally utilised for large, complicated systems when there is an emphasis on modelling and studying the relationships between various inherent variables in the system rather than the individual transactions between them [16]. Through the use of CLD, the approach enabled an effective way to represent the underlying structures of the system, allowing the understanding of behavioural patterns over time. SD modelling allows for improvisation of mental models, thereby contributing to better decision making in dynamic scenarios [17]. By allowing changes and experimentation in the mental models of the stakeholders, the approach further strengthens its decision-making capabilities. As a result of which, the approach has been useful in both qualitative and quantitative research in a variety of topics, including healthcare, management, policy, sociology, sustainability, market dynamics, process planning, and decision making [18]. In the realm of GHG mitigation, FOSSIL2 was one of the earliest models built for policy planning in the energy sector and was often used for studying the carbon abatement costs related to the Kyoto Protocol in the 1990s [19]. The SD approach enabled the model to capture the conformations of different possible interactions between the energy production sector and the energy consumption sector through the use of various intermediate divisions. Similarly, the holistic nature of the approach and its emphasis on cause-and-effect relationships resulted in various applications for studying the impact of policy and project implementations related to GHG mitigation in various specialised domains, such as the energy sector [20–23], transportation sector [11,24–26], iron and steel industry [27], cement industry, and as well as across all the domains in a particular region [28].

Despite its advantages, the growth in utilisation of SD is hampered due to the lack of awareness of its value among stakeholders [29]. For a model to be impactful, it needs to be implemented with the involvement of the important stakeholders during the model development stage. The dynamic hypothesis also needs to be validated by the stakeholders, which further decelerates the implementation of potent new models [30]. The majority of the SD models tend to be built in order to describe the dynamic aspects of the system, but their omission of fitting historic data and the lack of ability to provide passable quantitative forecasts impacts the acceptability of the models among the stakeholders. For testing policy interventions, it is also important to identify the most impactful parameters that would allow tracking of useful changes in the system [31].
3. Methodology

In the absence of any preceding review articles on the specific use of SD for carbon mitigation and policy evaluation in the cement industry, the selection of the literature was limited to the articles published between the years 2000 and 2020 in journals indexed by either Scopus or Web of Science (WoS). The year 2000 was chosen as the starting year in order to specifically focus upon studies that feature the most relevant strategies for CO₂ mitigation in the cement industry. The inclusion criteria for the articles in this review is to feature an application of the SD modelling approach specifically in the cement industry, and at least one of their objectives should be related to CO₂ mitigation, evaluation, or reduction. Taking these requirements into consideration, the following search query for title, abstract, and keywords was formulated:

\[
(((\text{system NEAR/0 dynamic*}) \text{ OR SD}) \text{ AND } ((\text{CO}_2 \text{ or carbon*}) \text{ AND emissi*}) \text{ AND } ((\text{mitigat* OR evaluat* OR reduct*}) \text{ OR (policy NEAR/0 analy*)}))
\]

which resulted in 500 records on WoS with 357 of them related to the domains of environmental sciences, green sustainable sciences, management sciences, or economics. Similarly, the same query was formatted for the Scopus search engine:

\[
(((\text{system pre/0 dynamic*}) \text{ OR SD}) \text{ AND } ((\text{CO}_2 \text{ or carbon*}) \text{ AND emissi*}) \text{ AND } ((\text{mitigat* OR evaluat* OR reduct*}) \text{ OR (policy pre/0 analy*)}))
\]

The query fetched 542 records on Scopus with 442 of them related to the aforementioned domains. Affixing “AND cement” to the search queries (1) and (2) on both platforms resulted in 13 and 9 records on WoS and Scopus, respectively, out of which 13 are unique records.

While SD modelling is relatively popular for policy analyses, as determined from Figure 1, the literature related to specifically utilising SD in the cement industry is relatively sparse. Therefore, overviewing the relevant articles from Table 1 would assist in determining the current state of the art and to scope for further improvements to this area. Articles 4, 8, and 9 from Table 1 are excluded in this review as they do not feature any specific models for the cement industry, but rather cumulate various industrial sources of carbon emissions into a single entity. Similarly, Article 5 is also excluded as it aims to provide a framework for modelling carbon emissions from the cement industry but does not contain an application of it. Furthermore, Article 7 is excluded as it does not fit the inclusion criteria of this review.

Table 1. List of unique articles returned by the search query on the Web of Science (WoS) and Scopus databases, as on 10 October 2020.

| No. | Reference | Article Title | Citation |
|-----|-----------|---------------|----------|
| 1   | Nehdi, Rehan and Simonovic (2004) | System dynamics model for sustainable cement and concrete: Novel tool for policy analysis | [32] |
| 2   | Anand, Vrat and Dahiya (2006) | Application of a system dynamics approach for assessment and mitigation of CO₂ emissions from the cement industry | [33] |
| 3   | Ansari and Seifi (2013) | A system dynamics model for analyzing energy consumption and CO₂ emission in Iranian cement industry under various production and export scenarios | [34] |
| 4   | Vafa-Arani, Jahani and Dashti (2014) | A system dynamics modeling for urban air pollution: A case study of Tehran, Iran | [35] |
Table 1. Cont.

| No. | Reference | Article Title | Citation |
|-----|-----------|---------------|----------|
| 5   | Song and Chen (2014) | A Life Cycle Modeling Framework for Greenhouse Gas Emissions of Cement Industry | [36] |
| 6   | Vargas and Halog (2015) | Effective carbon emission reductions from using upgraded fly ash in the cement industry | [37] |
| 7   | Zscheischler, Mahecha and Avitabile (2017) | Reviews and syntheses: An empirical spatiotemporal description of the global surface-atmosphere carbon fluxes: opportunities and data limitations | [38] |
| 8   | Li and Zhang (2017) | CO\(_2\) emission trends of China’s primary aluminum industry: A scenario analysis using system dynamics model | [39] |
| 9   | Zhang, Jiang, Liu, Tang and Wu (2018) | Can China Achieve its CO\(_2\) Emission Mitigation Target in 2030: a System Dynamics Perspective | [40] |
| 10  | Joker and Mokhtar (2018) | Policy making in the cement industry for CO\(_2\) mitigation on the pathway of sustainable development- A system dynamics approach | [41] |
| 11  | Ekinci, Kazancoglu and Mangla (2020) | Using system dynamics to assess the environmental management of cement industry in streaming data context | [42] |
| 12  | Tang, Wang and Dai (2020) | Exploring CO\(_2\) mitigation pathway of local industries using a regional-based system dynamics model | [12] |
| 13  | Proaño, Sarmiento and Figueredo (2020) | Techno-economic evaluation of indirect carbonation for CO\(_2\) emissions capture in cement industry: A system dynamics approach | [43] |

4. CO\(_2\) Mitigation Strategies in Cement Industry

The carbon footprint of cement plants is quantified through a number of reporting and measurement standards from organisations such as the Global Cement and Concrete Association (GCCA) and WBCSD [44,45]. As per the WBCSD’s Cement CO\(_2\) and Energy protocol, the emissions from the cement industry are classified under one of the following scopes:

- **Direct Emissions**, which encompasses all the point sources within the cement manufacturing process, such as production of clinker, which includes the emissions released during the process of calcination and fuel combustion for obtaining the thermal energy required for calcination.
- **Indirect Emissions**, which estimates the emissions released from the generation of purchased electricity, primarily utilised for powering the machines necessary for grinding and processing of materials.
- **Miscellaneous emissions**, which is considered as an optional reporting category that estimates the emissions from activities such as the transportation of raw materials and fuels to the cement plant.

Emissions are then estimated either through a calculation-based methodology, where the input parameters such as the clinker ratio, calorific value, and carbon content of fuels are used, or through a measurement-based methodology, where the concentration of CO\(_2\) is determined through analysis of exhaust flue gas.

In a cement plant, the majority of the direct CO\(_2\) emissions are from the endogenous chemical process called calcination, where the raw material, limestone (calcium carbonate), is converted into lime (calcium oxide) at a temperature of approximately 1000 degrees Celsius. In the cement process, the lime is further heated to 1450 degrees Celsius to form
clinker, which is primarily a mixture of calcium silicates (tricalcium silicate and dicalcium silicate). Worrell et al. [5] has stated that, based on the share of lime in the clinker, 0.5 kg of CO$_2$ is emitted during the process of calcination for every 1 kg of clinker produced. Being an endogenous reaction, calcination requires a significant amount of thermal energy, which is obtained through the combustion of fuels in the kiln. The resultant emissions from the fuel combustion depend on the fuel intensity and process efficiency. The electrical energy requirement in the cement manufacturing process is primarily for operating the machinery necessary for grinding and processing the clinker into cement. The thermal and electrical energy consumption across the major cement producing regions is further reported in Section 5.

Being a major source of industrial carbon emissions, several mitigations methods are currently employed in the cement industry at varying levels of adoption. The most recurring strategies featured among the literature in this domain from Table 1 are briefly described in this section.

4.1. WHR

The temperature of the flue gas originating in the cement kiln averages about 1200 °C and is often utilised in preheaters for improving the specific energy consumption (SEC) of the plant. However, the exhaust temperatures of the gas exiting from the pre-heater still ranges from 250 to 450 °C, carrying enough thermal energy to be used as the heat source in a Rankine cycle to generate electricity [46]. The impact of this mitigation approach on carbon emissions and financial sustainability depends on a range of factors, such as the grid emission factor, electricity unit prices, and the plant utilisation rate.

4.2. Blended Cements

Within the cement manufacturing process, production of clinker is the most energy-intensive and CO$_2$-emitting component. Clinker makes up to 95% of Portland cement, which is the most widely used variant of cement in the world. A portion of this clinker can be substituted by substances such as fly ash and blast furnace slag, without negatively impacting the properties of the Portland cement. This strategy relies on reducing the percentage of clinker in the cement for carbon mitigation. The potency of this strategy depends on the availability and cost of the substituent materials.

4.3. Alternate Fuels

As per the International Energy Agency, the cement industry is the third largest industrial consumer of energy and the majority of that is utilised for heating the kiln during the production of clinker. Coal is the most popular fuel used in the cement industry and this mitigation strategy involves replacing the high carbon fuels, such as coal, with substances such as refuse-derived fuels (RDF) or used tyres, which have a significantly lower CO$_2$ emission factor. Like blended cements, the mitigative potency of the strategy depends on the availability and cost of the replacement fuel.

4.4. Efficiency Improvements

By improving the efficiency of energy usage, a significant reduction in CO$_2$ emissions can be achieved through optimal use of fuel and electricity. In old cement plants, noticeable improvements can be achieved by replacing older equipment and tweaking the cement-making process to newer standards. This mitigation strategy requires a significant amount of investment and the payback period depends on the market price of the cement.

4.5. Carbon Capture and Storage

Carbon capture is a relatively new mitigation method, which utilises chemical solvents to absorb CO$_2$ from exhaust flue gases. It is estimated that there is a possibility of a 65–75% reduction of emissions in the cement industry through the usage of carbon capture methods [47]. Being a new technology, the implementation costs of this technology are
considerably higher compared to the rest of the mitigation methods in this list and the by-products generated through the process would incur additional costs for transportation and disposal [43].

5. Scope for Implementing Mitigation Strategies in the Cement Industry

Production of cement continues to be one of the most significant sources of industrial carbon emissions, and despite the availability of various mitigation options, their adoption rates have been largely inadequate. Figure 4 shows the changes in specific electrical energy consumption in the production of cement between 2010 and 2017 across various geographical regions. Despite active participation in the climate change protocols, regions such as North America and Europe have a comparatively less efficient production, highlighting the potential of electrical energy efficiency improvements in the reduction of carbon emissions in the cement industry. Similarly, Figure 5 depicts the thermal energy consumption in terms of megajoules (MJ) between the years 2012 and 2018, showing only marginal efficiency improvements in thermal energy use during production of clinker across the world, with the exception of the Commonwealth of Independent States (CIS).

![Figure 4](image1.png)

**Figure 4.** Specific electrical energy consumption of the cement industry in 2010 and 2017. Figure constructed based on the data available for public use in the GNR Light Report 2018 [48].

![Figure 5](image2.png)

**Figure 5.** Thermal energy consumption for production of clinker in the cement industry, 2012 and 2018. Figure constructed based on the data available for public use in the GNR Light Report 2018 [48].
Figures 6 and 7 depict the utilisation of alternate fuels and blended cements as a mitigation strategy. The global average of the clinker-to-cement ratio is at 0.79, with reports suggesting that ratio can be lowered to 0.7 for a significant reduction in emissions [49]. Figure 8 outlines the current deployment of WHR in the cement industry as a mitigation strategy in countries with the largest estimated potential for generating electricity through WHR, further accentuating the possibilities for future studies related to policy making for an even greater roll-out of mitigation projects.

**Figure 6.** Percentage of thermal energy generated using alternate fuels in cement industry in 2017. Figure constructed based on the data available for public use in the GNR Light Report 2018 [48].

**Figure 7.** Clinker-to-cement ratio across various geographical regions in 2017. Figure constructed based on the data available for public use in the GNR Light Report 2018 [48].
6. SD in the Cement Industry for GHG Mitigation

Cement production is a capital-intensive industry in which the cost of production depends upon numerous dynamic parameters, such as raw material procurement costs, electricity and fuel costs, workforce cost, logistics and transportation costs, and taxation. A typical cement plant can operate up to 50 years, thereby causing the financial sustainability of the production to be susceptible to changes in the previously specified parameters and as well as applicable policies [50]. The success of mitigation methods such as WHR and carbon capture in the reduction of GHG emissions is also determinant on factors such as the emission intensity of the local electrical grid and the characteristics of the utilised fuel, respectively. These mitigation projects, in turn, also influence the production costs of cement, specifically through changes in patterns of electrical and fuel usage, different tax scenarios, and as well as additional income, which might positively impact the rate of return on investment, possibly moulding the implementation of these mitigation projects to be more lucrative [51]. Sterman [52] states that the failure to incorporate important feedbacks into decision-making systems could potentially lead to policy resistances. Given this background, there is an opportunity to utilise the SD approach to aid the stakeholders in making informed decisions and foresee the various possibilities associated with each policy scheme.

Despite the growing popularity of utilising SD models for forecasting carbon emissions in various industrial domains, currently its application in the cement domain remains relatively limited. Section 3 lists the most relevant studies indexed in the WoS and Scopus databases that, within the cement industry, utilise the SD approach for either forecasting carbon emissions or evaluating various mitigation policies. The chosen studies are then explored based on their general scope, mitigation methods covered, modelling dimension, and experimental scenarios utilised.

Nehdi et al.’s [32] SD model aims to deduce the impact of clinker substitutes in reducing CO$_2$ emissions in the cement industry. The model assumes that the cement consumption is directly proportional to the growth rate of the gross domestic product (GDP) in developing countries, while directly proportional to the population in developed countries. The model utilises five subsections, as depicted in Table 2.
Table 2. Analysis of the subsystems in Nehdi et al.’s [32] SD model.

| Subsystem                        | Objective                                                                 |
|----------------------------------|---------------------------------------------------------------------------|
| Forecast                         | Forecasts the cement consumption based on population or GDP growth        |
| Fly ash concrete                 | Calculates the volume of fly ash concrete being utilised                 |
| Slag concrete                    | Calculates the volume of slag concrete being utilised                    |
| Ordinary Portland cement (OPC)   | Calculates the volume of OPC concrete being utilised                     |
| CO₂ emissions                    | Calculates the combined amount of emissions released from the cement industry |

Nehdi et al. [32] then utilises different scenarios to mimic various policy actions to determine the ratio of fly ash concrete, slag concrete, and OPC concrete that would fulfil the cement demand, which is determined by the forecast subsystem. Since the availability of fly ash and slag concrete depends on other sectors, such as coal power plants and the steel industry, additional cases are introduced in the simulation for calculating the availability of fly ash and slag for use within the cement industry. The first case assumes that better technologies are developed, which greatly improves the efficiency of the coal power plants and steel industry, thereby reducing the availability of fly ash and furnace slag. The second case assumes the wealth gap between developed and developing economies does not reduce, causing the developing countries to excessively rely on less efficient coal power plants, leading to a surplus quantity of fly ash and furnace slag. Depending on the case being considered, the availability of clinker substitutes is calculated at each time step, which could signify non-linear behaviour. The authors do not explicitly specify their model validation approach, but the results were simulated for various combinations of these scenarios and they are consistent with other studies, such as by Bosoaga et al. [53], who determined that blended cements have a potential to reduce CO₂ emissions in the industry by up to 20%. The authors also did not specify the details about the parameters used within the model.

Vargas et al.’s [36] study aims to determine the CO₂ emission reductions in the cement industry through the use of upgraded fly ash. The study improvises upon Nehdi et al.’s [31] approach by taking into account that the fly ash acquired from coal power plants does not always meet the quality requirements for being used as a replacement for clinker in the cement industry. Incompatible fly ash needs to go through an upgrading process before it can be used as a clinker replacement. The upgrading process requires additional thermal and electrical energy, and the model now incorporates this additional energy use when calculating the CO₂ emissions. The authors formulated the SD model for calculating and comparing the emissions between (1) the reference plant with no mitigation; (2) a cement plant that utilises the fly ash substitute; and (3) a cement plant that utilises an upgraded fly ash substitute, by utilising five stocks and flows and 14 converters. Vargas et al. [36] then utilises various lifecycle scenarios to simulate and compare the emissions between using OPC, fly ash cement, and upgraded fly ash cement. Additionally, emissions from the transportation of cement is also calculated in the model. The authors did not specify their model validation process but have included a sensitivity analysis of the results. The results from the simulation reiterate the conclusions drawn from the previous study, in that both fly ash and upgraded fly ash lower the emission intensity of the cement industry. Vargas et al.’s [37] model differs from the previous study in that it considers the cement production rate to be constant, as the study’s objective is to compare the mitigative effectiveness of the fly ash cement and upgraded fly ash cement when compared to OPC in a controlled setting. The authors did not explicitly define the various sub-systems utilised for their study.

Anand et al.’s [33] model aims to assess the reduction in CO₂ emissions under different mitigation scenarios. The model has a comparatively wider perspective than the preceding models, and now emphasizes the role of GDP and population growth in determining the cement demand and subsequently the carbon emissions. In contrast to the previous studies, it also incorporates thermal WHR as an additional mitigation approach apart from blended
cements. The model uses five different subsystems for various functions, as described in Table 3.

Table 3. Analysis of the subsystems in Anand et al.’s [33] model.

| Subsystem                     | Objective                                                                 |
|-------------------------------|---------------------------------------------------------------------------|
| Demand and production         | Estimates the cement demand and production based on variables such as population, GDP and exports |
| Energy consumption            | Estimates the electrical and thermal energy consumed for production of cement. The energy sources are further divided into conventional and renewable energy. WHR mitigation is incorporated as a source of thermal energy |
| Availability of slag and fly ash | Fly ash and furnace slag availability is calculated based on the regional consumption of coal and production of pig iron respectively |
| CO$_2$ emissions from plant operations | Calculates the total CO$_2$ emissions from the clinker production, electricity usage for machinery and the thermal energy use during the operation of the cement plants |
| CO$_2$ emissions from transportation | Calculates the CO$_2$ emissions from the transportation of raw materials to the cement plant and as well as the finished products to the destination |

The authors introduce variations to the cement demand and population at different time steps, adding on to the non-linear behaviour of the system. The amount of thermal waste heat available is calculated based on the total amount of clinker used and its related energy requirement for calcination. A converter is then utilised to set the percentage of waste heat that is recovered, as per the scenario tested. Similarly, the total slag and fly ash availability for clinker substitution is calculated based on the regional pig iron production and coal consumption. The use of alternate fuels is represented in the model through SEC set, using a converter as per the scenario. Based on the included diagrams, the model makes use of five stocks and flows for population, cement demand, cement production, coal consumption, and pig iron production. The authors have not explicitly listed details about all the exogenous and endogenous parameters used within the model. The model is validated using historical data and as well as a structural verification test and a dimension consistency test. The authors also conducted a sensitivity analysis, specifically focusing upon the impact of GDP and population on cement demand.

The study then considers three different scenarios—a baseline scenario, which is essentially the BAU condition where the cement demand, production, and population growth is considered to remain at the 2000 levels; and two modified scenarios, which considers the population growth to stabilise in 2020 and 2011, respectively. Four different policy options are then explored for each of the scenarios, which are (1) the share of renewable energy is set to 25% from 2010; (2) the specific energy consumption improves gradually from 3.06 to 2.9; (3) utilisation of thermal WHR is 30% of the total thermal energy requirement; and (4) a combination of these policies.

The study concludes with the results from the 20-year simulation in different scenarios under the hypothetical polices, as described previously. The model assumes that the thermal energy used in the clinker production is used exclusively from coal and has no provisions for considering the mitigation options, such as alternate fuels. The study only considers thermal WHR and efficiency improvements in the model with no provisions to evaluate the mitigative impact of electrical WHR and other mitigative options, such as alternate fuels.

Anasari and Seifi [34] developed a similar system of assessing CO$_2$ emissions in the cement industry, using the SD approach for evaluating the impact of energy price reforms and export policies in Iran. The SD model uses four different sub-systems, which are described in Table 4.
Table 4. Analysis of the subsystems in Anasari et al.’s [34] model.

| Subsystem          | Objective                                                                                                                                 |
|--------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Demand             | Similar to Anand et al.’s (2005) demand and production module, this calculates the cement demand based on the changes in population and GDP |
| Production         | Calculates the changes in production capacity based on the desired capacity, which takes into account the domestic demand and as well as exports |
| Energy consumption | Energy consumption is divided into thermal and electrical components and the requirement is calculated based on energy efficiency of the cement production in the region. Energy price is considered as a factor effecting the energy efficiency |
| CO₂ emission       | Calculates the total CO₂ emissions from clinker production, electricity generation, and fuel consumption                                     |

The primary objective of the model has been to simulate the impact of subsidy reforms on fuel and electricity on the cement industry and how different corrective policies, such as blended cements and WHR, will reduce the carbon emissions. The authors modelled the industry stakeholder behaviour with respect to implementation of mitigation measures to improve the specific energy and electricity consumption based on an exogenous parameter—energy tariff. The model calculates the impact of mitigation methods through various plant efficiency scenarios. Based on the included stock-and-flow diagrams, the implementation utilises 11 stocks and 17 flows across four subsystems. The authors explicitly state the use of 51 parameters in the entire model, with 34 of them endogenous and the remaining 17 exogenous. The model was then validated based on the historical data of GDP growth rate, natural gas utilisation rate, and prices of fuel and electricity.

These production scenarios are then coupled with energy efficiency scenarios mimicking the impact of subsidy reforms, which are (1) the existing efficiency in Iran as of 2013; (2) a moderate efficiency with lower emission intensity from energy use; and (3) the high efficiency, with a significant portion of electricity requirement, is met by WHR and increased production of blended cements. Unlike the previous studies, Anasari et al.’s [34] model does not calculate the availability of fly ash and furnace slag for use in blended cements and combines electrical efficiency improvements and WHR into a single metric, limiting the scope for experimentation.

Jokar and Mokhtar [41] built upon the existing research models to incorporate an economic and social subsystem for calculating manufacturer profit based on production costs and market pricing. The authors evaluate the impact of three major mitigation techniques—WHR, clinker substitution, and alternate fuel use—in reducing CO₂ emissions in the Iranian cement industry. The model utilises six subsystems, as described in Table 5.

Table 5. Analysis of the subsystems in Jokar and Mokhtar’s [41] model.

| Subsystem             | Objective                                                                                                                                 |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Cement production capacity | Calculates the cement production based on capacity utilisation, nominal capacity and rate of capacity expansion                          |
| Clinker production capacity | Calculates the clinker production based on the cement capacity and the average clinker ratio for accounting blended cements            |
| Energy consumption    | Utilises thermal and electrical SEC for calculating the energy requirement of the cement industry                                         |
| CO₂ emissions         | Calculates the total CO₂ emissions based on clinker production and the average emission intensity of the electricity and fuel used for production |
| Economic module       | Industry profits are calculated by determining production costs and manufacturer income through cement market prices                  |
| Social module         | Determines the rate of capacity expansion based on manufacturer profit and investment costs. Additionally, it calculates the labour requirement |
The model then employs two primary scenarios—a BAU with 89% utilisation of the cement production capacity, and a BAU with 100% utilisation of the production capacity. These scenarios are combined with one of the following policies: (1) a reference production trend without any mitigation; (2) utilising WHR for generating electricity and completely selling it to the external grid; (3) using waste material as alternate fuels; and (4) clinker substitution. The model then allows experimentation through setting different values for the policy options. The authors represent the mitigation project’s effectiveness in their model by calculating the emission intensity of the fuel and clinker production, as per the policy scenario being tested. The respective investment costs for each mitigation method is incorporated in their social module for evaluating the manufacturer profit. Based on the included stock-and-flow diagrams, the authors have utilised 5 stocks and 10 flows in their model. The model was validated based on the historical data of clinker and cement production, respectively, and a sensitivity analysis was conducted by examining the changes in production costs based on fuel and electricity prices. The author simulated the outcomes by considering that 15% of the thermal energy is obtained by alternate fuels and 15% of the clinker is substituted by a different material. The study concludes by determining that clinker substitution is the most effective method for emission reductions while WHR is effective for manufacturer profits and labour engagement.

Jokar et al.’s [41] model improvises on the existing models in this domain by including an economic analysis of the mitigation policies. It also utilises a social module for calculating the employment requirement of the industry under different policies. However, the model does not calculate the availability of clinker substituents, which is the most significant hurdle in adapting blended cements as a mitigation approach [49]. The model also does not consider the investment costs of implementing mitigation techniques despite simulating the economic impact of the policies.

Tang et al. [12] aims to provide a framework for building SD models in mitigation studies with an emphasis on inter-regional complementarity, where the carbon emissions of a region is forecasted while taking into account its relationship with the neighbouring regions and the carbon flow between them. The framework recommends division of any industrial emission model into three subprocesses, namely demand, supply, and emission calculations, as described in Table 6. As an included case study, the Chongqing (China) cement industry has been modelled and simulated under two different scenarios, BAU and low-carbon consumption. The low-carbon scenario assumes a higher amount of clinker substitution, better electrical efficiency, and increased production capacity. The authors incorporate the use of clinker substitutes, fuel substitution, and waste heat recovery through exogenous parameters for the respective utilisation ratios whose values are chosen based on the scenario being tested. Based on the included stock-and-flow diagram, the authors have utilised three stocks and flows in their model for GDP, cement consumption per capita, and total emissions from the cement industry. The authors have built their model under an assumption that the policy scenario remains constant throughout the simulation period. The model was validated through dimensional consistency test, structural verification, and historic data. Then sensitivity analysis was conducted focusing on parameters such as clinker ratio, WHR utilisation rate, alternate fuel utilisation rate, and emission intensity. The study concludes highlighting the benefits of modelling from an inter-regional perspective and the possibility of utilising this framework in other industries. However, the study does not consider the economic impact of implementing a low-carbon scenario on the industry.

Ekinci et al. [42] takes a holistic approach in studying the long-term impact of cement industries on the regional air pollution by emphasising more the industry’s relationship with aspects such as population growth and its related effects, such as demand for new building construction. The study aims to combine all the external variables that indirectly contribute to air pollution through the cement industry. Unlike the other studies in this section, this model excludes the technicalities of cement production by not individually calculating emissions from each module in the production process, such as electricity and fuel consumption, and clinker production. The model calculates emissions from the
cement industry by determining the cement production capacity based on yearly GDP and construction activity. The model does not directly evaluate any specific mitigative method but incorporates a single exogenous variable for representing the reduction in emissions through policy scenario. The authors did not provide any stock-and-flow diagrams or parameter list to determine the model complexity. The model was validated using one-way ANOVA test and the study concludes by stating the correlation between the demand for construction of new buildings with cement production and regional air pollution. Similar to Vargas et al. [37], this study also does not explicitly describe the various subsystems utilized in their SD model.

Table 6. Analysis of the subsystems in Tang et al.’s [12] model.

| Subsystem         | Objective                                                                 |
|-------------------|---------------------------------------------------------------------------|
| Demand            | Calculates the cement demand from the local population as well as additional external demand from adjacent regions |
| Supply            | Calculates the inter-regional cement production based on the demand while taking into consideration the technological differences within the adjacent region, i.e., differences in specific energy consumption |
| CO₂ emission      | Calculates emissions based on net energy used for cement production as determined in the supply subsystem |

Proaño et al. [43] evaluates the technical and economic aspects of using indirect carbonation (carbon capture) method during the production of clinker. In contrast to the other models in this section, the author uses a single reference production plant for the study instead of a macrolevel approach to the cement industry. The model includes a sub-system to simulate the financial impact of implementing the carbon capture method in the cement plant along with the additional income that could be generated through the sale of by-products created during the mitigation process. The remaining modules featured in the system are described in Table 7. While the study solely focuses on the carbon capture method, it considers the impact of the initial investment costs of implementation, which is one of the most significant factors influencing the adoption rates in the cement industry. The authors have explicitly specified that the SD approach was chosen in order to deal with the complexities related to modelling economic behaviour that is not only dependent on initial investment and operational costs, but also government policy and shifting market conditions. The model was evaluated through structural verification at each step of model building and as well as using historic data for GDP and cement demand.

Table 7. Analysis of subsystems in Proaño et al.’s [43] model.

| Subsystem                  | Objective                                                                                                                                                                                                 |
|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cement demand              | Calculates the cement demand based on the regional GDP growth                                                                                                                                              |
| Cement production          | Calculates the cement production by factoring in cement demand and production capacity of the reference plant                                                                                             |
| CO₂ estimation and capture | Calculates the CO₂ capture rate and by-product production based on the amount of cement produced and type of carbon solvent used. The module assumes the clinker content in cement as a static value of 73.7% |
| Costs and profit           | Calculates the production cost based on energy and fuel consumption, raw material requirements, administrative and maintenance costs. It then estimates the profits through the sale of cement and by-product sales as well as emission subsidies |

The model incorporates the mitigation method through a dedicated subsystem in their model that calculates the CO₂ emission capture potential based on the available CO₂ from cement production and as well as the market demand for the by-products generated through the mitigation process. Based on the included stock-and-flow diagrams for their subsystems, the authors have utilised 11 stocks and 14 flows in their model. The study then considers various technical scenarios where the carbon capture module utilises either
sodium-, barium-, or calcium-based solvents for mitigating CO₂ emissions and compares the results with the base BAU scenario. These scenarios are further evaluated under different market and policy conditions and concluded that carbon taxation would have a great impact on promoting the use of carbon-capture technologies to achieve the emission reduction goals within the cement industry.

For a model to be a promising decision-making and analytic tool, it should facilitate the analysis of the most prospective mitigation techniques currently available in the cement industry. Depending upon the specific objectives, the scope of the model plays a great role in determining its applicability among the various stakeholders. The models that incorporate the economic analysis of implementing mitigation projects further improves their pertinence in decision making as the payback period of the mitigation adoption costs often depends on various dynamic factors, such as energy and maintenance costs. Taking these points into consideration, Table 8 summarises the previously described studies. None of the overviewed studies present the entire set of model equations, which would have fostered replicability and allowed for practical evaluation of the models. The complexity of the models, in the form of the number of stocks and flows used, is determined based on either explicit information provided by the authors or through the included stock-and-flow diagrams and model equations. The table also lists the mitigation methods explored in each study, either through an auxiliary parameter or a policy scenario. With the exception of Nehdi et al. [32] and Vargas et al. [37], all the studies in the list have presented the validation approach used for their models.

Table 8. Summary of the overviewed studies.

| Reference      | Primary Objective                                                                                                                                                                                                 | Scope                                                                 | Complexity   | Model Equations  | Model Validation | Mitigation Methods Featured or Facilitated | Analysis of Economic Impact of Mitigation Policies on Cement Industry |
|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|--------------|------------------|------------------|------------------------------------------|------------------------|
| Nehdi et al.  | To forecast the impact of replacing clinker with substitutes such as fly ash and slag on carbon emissions in the cement industry and provide a tool for analysing policy scenarios.  | Coalescence of regional cement industry; estimates carbon emissions from cement industry by calculating the total regional cement production based on demand for different blended cements | Undisclosed  | None             | Unspecified       | Clinker substitution                      | No                     |
| Anand et al.  | To estimate the total CO₂ emissions from the cement industry in India                                                                                                                                                                                                 | Coalescence of regional cement industry; estimates carbon emissions based on total energy consumption in the cement industry as well as the emissions from transporting raw materials. Also calculates the availability of clinker substitutes that can be used for reducing emissions | 5 stocks 5 flows | Partially described | Validated using historical data, structural verification test and dimensional consistency test | Clinker substitution, alternate fuels, and WHR | No                     |
| Ansari et al. | To analyse carbon emissions from the Iranian cement industry under different policy scenarios                                                                                                                   | Coalescence of regional cement industry; estimates carbon emissions based on thermal and electrical efficiency factors of cement production. Calculates the energy demand of cement industry based on the regional energy prices | 11 stocks 17 flows | Partially described | Validated using historical data            | Thermal and electrical efficiency improvements | No                     |
### Table 8. Cont.

| Reference         | Primary Objective                                                                 | Scope                                                                 | Complexity | Model Equations | Model Validation | Mitigation Methods Featured or Facilitated | Analysis of Economic Impact of Mitigation Policies on Cement Industry |
|-------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|------------|-----------------|------------------|---------------------------------------------|-----------------------------------------------------------------------|
| Vargas et al. [37]| To estimate the reductions in carbon emissions when using upgraded fly ash in the cement industry | Single reference plant; calculates emissions from production of cement, transportation of raw materials, and as well as process of upgrading fly ash | 5 stocks 5 flows 14 converters | Partially described | Unspecified | Clinker substitution | No |
| Jokar et al. [41] | To simulate the impact of mitigation measures on carbon emissions in the Iranian cement industry | Coalescence of regional cement industry; estimates carbon emissions based on the total energy consumed and clinker ratio. Also calculates the production costs of cement based on the energy consumption and as well as non-energy factors | 5 stocks 10 flows | None | Validated using historical data | Clinker substitution, alternate fuels, and WHR | Yes |
| Tang et al. [12]  | To present a framework for estimating carbon emissions in an “inter-regional context between neighbouring regions” and applying it on cement industry as a case study | Coalescence of regional cement industry; estimates carbon emissions based on the fuel and electricity consumption of the cement industry | 3 stocks 3 flows | Partially described | Validated using historical data, structural verification test and dimensional consistency test | Clinker substitution, alternate fuels, and WHR | No |
| Ekinci et al. [42] | To predict the contribution of cement industry to the regional air pollution levels through a holistic approach | Coalescence of regional cement industry; calculates the contribution of cement production to regional air pollution using streaming data of pollution metrics and economic activity | Undisclosed | None | Validated using one-way ANOVA test | None, study excludes technicalities of cement production | No |
| Proaño et al. [43] | To evaluate the use of indirect carbonation mitigation approach in cement industry for emission reductions | Single reference plant; calculates the carbon emissions based on the cement produced and reductions related to using indirect carbonation method to capture CO₂ from post-process flue gas exhaust. Incorporates the cost of implementation and maintenance of carbon capture approach and as well as the sale of by-products | 11 stocks 14 flows | None | Validated using historical data and structural verification test | Carbon capture | Yes |

#### 7. Gaps in the Existing Literature

With the exception of Jokar et al. [41] and Proaño et al. [43], the remainder of the studies stated in the previous section do not simulate the financial implications of policies and primarily focus on forecasting the carbon emissions as recapitulated in Table 8. Determining the economic viability of adopting a mitigation method is the foremost concern of
the industry stakeholders as strategies such as WHR and efficiency improvements incur significant investment costs that would impact the profit margins.

Among the studies summarised in Section 6, none of them featured all of the available mitigation options for the cement industry, with Nehdi et al. [32] and Vargas et al. [37] solely focusing on clinker substitution, Anand et al. [33] and Anasari et al. [34] omitting alternate fuels, Jokar et al. [41] excluding efficiency improvements, and Proaño et al. [43] exclusively studying the impact of carbon capture strategy. This prevents experimentation with scenarios in which the industry adopts multiple mitigation strategies, which have different costs of implementation.

Additionally, all the aforementioned models, with the exception of Proaño et al. [43], simulate the mitigation impact on the cement industry at a macro scale, which is adequate for analysing the general outcomes in a large region from the perspective of a policy-maker but lacks the flexibility for being utilised by the industry stakeholders. A significant percentage of the global cement companies operate a single production plant with many plants exclusively producing clinker or operating grinding mills [54]. The existing models would not be effective in realistically determining both the mitigation and financial impact of policies on such plants. Even companies that own multiple plants often take decisions regarding implementation of mitigation projects on a per-plant basis, considering that the availability and costs of resources for mitigation, such as fly ash, furnace slag, or refuse-derived fuels as a fuel replacement, varies discernibly for each plant [55]. Previous studies have also ignored the requirements and feedback from mitigation methods, which would have a decisive impact on determining the viability of the projects. While Jokar et al. [41], Anasari et al. [34], and Anand et al. [33] feature WHR mitigation in their studies, they ignore the input conditions for calculating the energy recovered. Depending upon various factors, cement plants seldom operate at full utilisation capacity and this would significantly impact the amount of energy recovered through WHR. For reference, the average utilisation rate in the Indian cement industry was 67% in 2019, with varying fluctuations among individual cement plants [56]. Apart from Proaño et al. [43], none of the other studies consider the impact of carbon capture, a relatively new mitigation approach in which the CO₂ in the exhaust gases is captured through the usage of chemical solvents. This mitigation approach is currently gaining traction within the cement industry with several plants implementing it on an experimental basis [57].

8. Considerations for Future Work

Given the strengths of the SD approach in handling complex systems with numerous feedback loops and non-linear relationships, it could be reasonable to address the identified gaps using this technique. The future studies could be reinforced through incorporation of feedback from multiple mitigation projects and their substantial cost-and-benefit analysis under various fluctuating market conditions and policy scenarios. Such implementations of SD approaches would be comparatively efficacious in determining plant viability and contribute to resolving decision-making dilemmas.

In order to address the gaps and increase the applicability of the models in the scenarios relevant in the present, the following improvements could be considered and evaluated when designing the SD models for the cement industry in future studies:

1. Inclusion of dedicated sections/subsystems in the models to capture the functionality of each mitigation method in greater detail. It would potentially enable detailed analysis on the efficacy of each mitigation method under different system states and policy scenarios. For example, when determining the potency of WHR or blended cements in reducing carbon emissions, inputs from variables such as plant utilization rate and fly-ash procurement costs play an important factor. Furthermore, it would allow explorative analysis of utilizing multiple mitigation techniques in the same plant. In scenarios of low grid emission factor and high electricity tariffs, WHR systems could still assist in reducing carbon emissions by contributing to the electricity requirement of a carbon capture plant and making its operation financially viable.
(2) In-depth representation of feedback loops and causal patterns between mitigation methods and the rest of the system. For example, feedback from mitigation methods like WHR and carbon capture, whether it is through captive power generation or revenue from the by-products of carbon capture, could significantly influence payback periods of the respective mitigation projects. Such an inclusion will improve the value of the SD model as a decision-making tool among the decision makers. Integration of specific parameters, such as utilisation rate, which varies throughout a cement plant’s lifecycle, would not only improve the accuracy of the emissions forecast, but would also be vital in calculating the recoverable heat energy available in the exhaust flue gases for generating electricity through the WHR system.

(3) Emphasis on tuning the model boundary to make it applicable to stakeholders in individual cement plants. Models built solely from the policymakers’ perspective offer insufficient value in terms of decision making on a plant-to-plant basis. By providing the necessary tools to industrial stakeholders, it could potentially accelerate the rate of implementation of new mitigation projects in the cement industry.

(4) Thorough cost–benefit analysis of implementing various mitigation projects and their consequent lifecycles. Traditional approaches towards cost–benefit analyses do not provide a dynamic view that explores all the relationships between the components relevant to the analysis over time. A cost–benefit analysis in conjunction with a systems thinking approach would strengthen the model’s role as a decision-support tool.

9. Limitations

The scope of this review is limited to studies featured in the WoS and Scopus databases, as a result of which the literature featured in this document cannot be considered as a complete list of the available literature on this topic. Additionally, the featured studies are only compared on the basis of information provided within the selected literature. The omission of necessary information to replicate the models hinders the ability to replicate and practically evaluate the implementations under similar conditions and datasets.

10. Conclusions

The various applications of SD modelling for evaluating CO$_2$ mitigation strategies were comparatively overviewed, with an emphasis on the cement industry. All the available mitigation approaches currently employed in the cement industry were described in Section 5 along with their current state of implementation, underscoring the potential for further research in this domain. SD models and their use in policy evaluation and emission forecasts across multiple domains is presented while focusing on the studies within the cement industry. Furthermore, the gaps in existing literature are presented, along with considerations for future work to aid further investigations and improvements in studies that employ an SD approach for evaluation of mitigation methods.

The growing conscience on the effects of CO$_2$ emission reinforces the global focus on carbon-intensive industrial sectors, such as the cement industry, highlighting the need for effective decision-making tools for both policy makers and industry stakeholders for analysing and choosing the appropriate mitigation strategies that would maximise the CO$_2$ reduction while being economically sustainable. The complexity and uncertainty of the factors that impact the profitability of cement industry tends to vary throughout the lifecycle of the mitigation projects currently under consideration, thereby making it worthwhile to explore holistic system models. In order to facilitate policy planning for achieving the goals set by various inter-governmental bodies for carbon mitigation in cement industry, which is about a 20–25% reduction in carbon emissions, there is a scope for an integrated model that encompasses all of the previously discussed mitigation options in the preceding sections and intimately studies the financial implications of their implementation and maintenance costs. Such a model could be also utilised for studying the behavioural patterns regarding which mitigation options would be favoured under
a specific set of market conditions and consequently provide potential inputs for further policy tweaks. By emphasizing an individual reference plant and not the entirety of the cement industry, the SD approach could potentially enable stakeholders to determine the viable combination of mitigation methods that can be utilised to optimise the balance between mitigation effectiveness and overall profit margins. Additionally, such a study could also be adapted to other industrial domains with their own distinct mitigation methods.

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References
1. Rubenstein, M. Emissions from the Cement Industry. Available online: http://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/ (accessed on 9 October 2020).
2. Metz, B.; Davidson, O.; De Coninck, H.; Loos, M.; Meyer, L. Carbon Dioxide Capture and Storage. Available online: https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/ (accessed on 10 October 2020).
3. Fonta, P. The “Paris Agreement” on Climate Change: An Opportunity for Cement Sector to Further Reduce Its CO₂ Emissions. In Proceedings of the 2017 IEEE-IAS/PCA Cement Industry Technical Conference, Calgary, AB, Canada, 21–25 May 2017.
4. Bigger Climate Action Emerging in Cement Industry. Available online: https://unfccc.int/news/bigger-climate-action-emerging-in-cement-industry (accessed on 10 October 2020).
5. Worrell, E.; Price, L.; Martin, N.; Hendriks, C.; Meida, L.O. Carbon Dioxide Emissions from the Global Cement Industry. Annu. Rev. Energy Environ. 2001, 26, 303–329. [CrossRef]
6. Liu, X.; Hang, Y.; Wang, Q.; Zhou, D. Flying into the Future: A Scenario-Based Analysis of Carbon Emissions from China’s Civil Aviation. J. Air Transp. Manag. 2020, 85, 101793. [CrossRef]
7. Zhu, L.; He, L.; Shang, P.; Zhang, Y.; Ma, X. Influencing Factors and Scenario Forecasts of Carbon Emissions of the Chinese Power Industry: Based on a Generalized Divisia Index Model and Monte Carlo Simulation. Energies 2018, 11, 2398. [CrossRef]
8. Zhou, M.; Zhou, M.; Pan, Y.; Chen, Z.; Zeng, J. Multi-Agent-Based Simulation for Policy Evaluation of Carbon Emissions. In Theory, Methodology, Tools and Applications for Modeling and Simulation of Complex Systems; Springer: Singapore, 2016; pp. 265–272.
9. Wu, J.; Mohamed, R.; Wang, Z. An Agent-Based Model to Project China’s Energy Consumption and Carbon Emission Peaks at Multiple Levels. Sustainability 2017, 9, 893. [CrossRef]
10. Li, Z.T.; Akhavian, R. Carbon Dioxide Emission Evaluation in Construction Operations Using DES: A Case Study of Carwash Construction. In Proceedings of the 2017 Winter Simulation Conference (WSC), Las Vegas, NV, USA, 3–6 December 2017.
11. Procter, A.; Bassi, A.; Kolling, J.; Cox, L.; Flanders, N.; Tanners, N.; Araujo, R. The Effectiveness of Light Rail Transit in Achieving Regional CO2 Emissions Targets Is Linked to Building Energy Use: Insights from System Dynamics Modeling. Clean Technol. Environ. Policy 2017, 19, 1459–1474. [CrossRef]
12. Tang, M.; Wang, S.; Dai, C.; Liu, Y. Exploring CO₂ Mitigation Pathway of Local Industries Using a Regional-Based System Dynamics Model. Int. J. Inf. Manag. 2020, 52, 102079. [CrossRef]
13. Sterman, J. Business Dynamics: Systems Thinking and Modeling for a Complex World with CD-ROM; McGraw-Hill Professional: New York, NY, USA, 2000.
14. Kunc, M. System Dynamics: A Behavioral Modeling Method. In Proceedings of the 2016 Winter Simulation Conference (WSC), Washington, DC, USA, 11–14 December 2016.
15. Bala, B.K.; Arshad, F.M.; Nob, K.M. System Dynamics: Modelling and Simulation, 1st ed.; Springer: Singapore, 2016.
16. Koelling, P.; Schwandt, M.J. Health Systems: A Dynamic System—benefits from System Dynamics. In Proceedings of the Winter Simulation Conference, Orlando, FL, USA, 4 December 2005.
17. Doyle, J.K.; Ford, D.N. Mental Models Concepts for System Dynamics Research. Syst. Dyn. Rev. 1998, 14, 3–29. [CrossRef]
18. Kunc, M.; Mortensen, M.J.; Vidgen, R. A Computational Literature Review of the Field of System Dynamics from 1974 to 2017. J. Simul. 2018, 12, 115–127. [CrossRef]
19. Naill, R.F.; Belanger, S.; Klinger, A.; Petersen, E. An Analysis of the Cost Effectiveness of U.S. Energy Policies to Mitigate Global Warming. Syst. Dyn. Rev. 1992, 8, 111–128. [CrossRef]
20. Feng, Y.Y.; Chen, S.Q.; Zhang, L.X. System Dynamics Modeling for Urban Energy Consumption and CO\textsubscript{2} Emissions: A Case Study of Beijing, China. *Ecol. Model.* 2013, 252, 44–52. [CrossRef]

21. Sun, W.; Wang, J.; Ren, Y. Research on CO\textsubscript{2} Emissions from China’s Electric Power Industry Based on System Dynamics Model. *Int. J. Ind. Syst. Eng.* 2016, 22, 423.

22. Sayesel, A.K.; Hekimoğlu, M. Exploring the Options for Carbon Dioxide Mitigation in Turkish Electric Power Industry: System Dynamics Approach. *Energy Policy* 2013, 60, 675–686. [CrossRef]

23. Robalino-Lopez, A.; Mena-Nieto, A.; Garcia-Ramos, J.E. System Dynamics Modeling for Renewable Energy and CO\textsubscript{2} Emissions: A Case Study of Ecuador. *Energy Sustain. Dev.* 2014, 20, 11–20. [CrossRef]

24. Han, J.; Hayashi, Y. A System Dynamics Model of CO\textsubscript{2} Mitigation in China’s Inter-City Passenger Transport. *Transp. Res. D Transp. Environ.* 2008, 13, 298–305. [CrossRef]

25. Han, J.; Bhandari, K.; Hayashi, Y. Evaluating Policies for CO\textsubscript{2} Mitigation in India’s Passenger Transport. *Int. J. Urban Sci.* 2008, 12, 28–39. [CrossRef]

26. Barisa, A.; Rosa, M. A System Dynamics Model for CO\textsubscript{2} Emission Mitigation Policy Design in Road Transport Sector. *Energy Procedia* 2018, 147, 419–427. [CrossRef]

27. Kim, K.-S.; Cho, Y.-J.; Jeong, S.-J. Simulation of CO\textsubscript{2} Emission Reduction Potential of the Iron and Steel Industry Using a System Dynamics Model. *Int. J. Precis. Eng. Manuf.* 2014, 15, 361–373. [CrossRef]

28. Wen, L.; Bai, L.; Zhang, E. System Dynamic Modeling and Scenario Simulation on Beijing Industrial Carbon Emissions. *Environ. Eng. Res.* 2016, 21, 355–364. [CrossRef]

29. Rumeser, D.; Emsley, M. Key Challenges of System Dynamics Implementation in Project Management. *Procedia Soc. Behav. Sci.* 2016, 230, 22–30. [CrossRef]

30. Pagoni, E.G.; Georgiadis, P. System Dynamics Approaches to Public-Private Partnerships: A Literature Review. *Syst. Res. Behav. Sci.* 2020, 37, 277–291. [CrossRef]

31. Uriona, M.; (Saartjie) Grobbelaar, S.S. Innovation System Policy Analysis through System Dynamics Modelling: A Systematic Review. *Sci. Public Policy* 2019, 46, 28–44. [CrossRef]

32. Nehdi, M.; Rehan, R.; Simonovic, S.P. System Dynamics Model for Sustainable Cement and Concrete: Novel Tool for Policy Analysis. *ACI Mater. J.* 2004, 101, 216–225.

33. Anand, S.; Vrat, P.; Dahiya, R.P. Application of a System Dynamics Approach for Assessment and Mitigation of CO\textsubscript{2} Emissions from the Cement Industry. *J. Environ. Manag.* 2006, 79, 383–398. [CrossRef] [PubMed]

34. Ansari, N.; Seifi, A. A System Dynamics Model for Analyzing Energy Consumption and CO\textsubscript{2} Emission in Iranian Cement Industry under Various Production and Export Scenarios. *Energy Policy* 2013, 58, 75–89. [CrossRef]

35. Vargas, J.; Halog, A. Effective Carbon Emission Reductions from Using Upgraded Fly Ash in the Cement Industry. *Energy Policy* 2014, 61, 2649–2653. [CrossRef]

36. Jokar, Z.; Mokhtar, A. Policy Making in the Cement Industry for CO\textsubscript{2} Mitigation on the Pathway of Sustainable Development- A System Dynamics Approach. *J. Clean. Prod.* 2015, 103, 948–959. [CrossRef]

37. Ansari, N.; Seifi, A. System Dynamics Model for the Cement Sector Market and Supplier Analysis. Available online: https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/report_waste_heat_recovery_for_the_cement_sector_market_and_supplier_analysis (accessed on 10 October 2020).

38. Anderson, S.; Newell, R. Prospects for Carbon Capture and Storage Technologies. *Annu. Rev. Environ. Resour.* 2004, 29, 109–142. [CrossRef]
48. GNR Project. Available online: https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/ (accessed on 23 February 2021).
49. Clinker Substitution. Available online: https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/ (accessed on 10 October 2020).
50. Boyer, M.; Ponssard, J.P. Economic Analysis of the European Cement Industry. SSRN Electron. J. 2013. [CrossRef]
51. Hedman, B. Waste Heat Recovery in Turkish Cement Industry Review of Existing Installations and Assessment of Remaining Potential; World Bank: Washington, DC, USA, 2019.
52. Sterman, J.D. All Models Are Wrong: Reflections on Becoming a Systems Scientist. Syst. Dyn. Rev. 2002, 18, 501–531. [CrossRef]
53. Bosoaga, A.; Masek, O.; Oakey, J.E. CO₂ Capture Technologies for Cement Industry. Energy Procedia 2009, 1, 133–140. [CrossRef]
54. Peter Edwards, Global Cement Magazine. Global Cement Top 100 Report 2017–2018. Available online: https://www.globalcement.com/magazine/articles/1054-global-cement-top-100-report-2017-2018 (accessed on 10 October 2020).
55. LafargeHolcim Publishes Sustainability Report. 2018. Available online: https://www.lafargeholcim.com/lafargeholcim-publishes-sustainability-report-2018 (accessed on 10 October 2020).
56. Global Cement Staff. Indian Cement Sector Operating at 67% Capacity Utilisation Rate. Available online: https://www.globalcement.com/news/item/9503-indian-cement-sector-operating-at-67-capacity-utilisation-rate (accessed on 10 October 2020).
57. LafargeHolcim Launches Carbon Capture Project in Canada. Available online: https://www.lafargeholcim.com/lafargeholcim-launch-carbon-capture-project-canada (accessed on 10 October 2020).