Master's Thesis – master Sustainable Development- track Energy & Materials

Cement Demand Forecasting:

Developing a Comprehensive Conceptual Framework for Forecasting Cement Demand in EU27 countries.

Author: Orestis Riginos Kiriakidis

Supervisor: Dr. ir. Wina Crinjs-Graus

2nd Assessor: Dr. Robert Harmsen

Utrecht University

Summary

Addressing the transition in energy-intensive sectors, such as the cement industry, is crucial for achieving sustainability and mitigating climate change. Despite this urgent focus on sustainability, specific measures to guide this transition within the cement industry remain undeveloped. This thesis investigates the dynamics of cement demand within the EU27 region, aiming to identify key drivers that policymakers can target to facilitate a successful transition toward more sustainable practices in the industry.

The study begins by analysing historical trends and correlations in cement demand driver indicators within the EU27 region and at the country level. These indicators encompass both the direct use of cement in construction activities and the broader socio-economic climate influencing the construction and cement industries. A particular focus is placed on long-term energy models featuring a module dedicated to the cement sector. This approach is for its comprehensive nature, integrating in integrating energy demand projections within sector-specific analysis. The detailed analysis includes three models: IMAGE, FORECAST, and China Energy and Emissions Paths, to identify key considerations for cement demand forecasting.

By synthesizing the insights from these two analyses, a comprehensive framework for forecasting cement demand in EU27 countries was developed and tested through a case study in the Netherlands. The framework incorporates both bottom-up (physical demand drivers) and top-down (socio-economic drivers) variables. The framework was specifically modelled for the residential building sector due to limited publicly available data on non-residential buildings average floor areas and construction GVA forecasts. The forecasted cement demand for the Netherlands ranged from 540 ktonnes to 1183 ktonnes by 2050, depending on the explored scenarios.

The findings highlight the complex interplay between socio-economic factors with end-user activities, cement intensity factors, and structural changes in the construction and cement industries that interact to shape cement demand. Population growth emerges as a significant driver of cement demand in the model, while household type also plays a crucial role. The research concludes by emphasizing the need for policymakers to incentivize multi-dwelling unit developments, support advanced materials and technologies that reduce cement content while maintaining structural integrity, and align land-use and zoning policies with these objectives.

Preface

This thesis represents the culmination of my studies in the Master's program in Sustainable Development, specializing in Energy and Materials, at Utrecht University.

First of all, I would like to express my deepest gratitude to my supervisor, Dr. ir. Wina Crinjs-Graus, for her invaluable support, ongoing guidance, and insightful feedback throughout this thesis. Her expertise and encouragement have been crucial in guiding my research and have ensured that I consistently found fulfilment in conducting this study.

I am also grateful to Daniel Duffy for generously participating in the interview conducted for this research and to Stefan Berner Beltran for facilitating this opportunity. Daniel's willingness to share his expertise and perspectives significantly enriched this study.

Finally, I wish to thank all my friends and family for their encouragement, understanding, and patience through this journey.

Orestis Kiriakidis

Utrecht, August 2024

Table of Contents

1 Introduction

The cement industry is a major contributor to global CO_2 emissions, with a staggering 2.42 $GtCO_2$ produced in 2022 alone, accounting for nearly 27% of the total direct CO_2 emissions from the industrial sector (Richard Simon et al., 2023). The European Cement Association (2023) reported that global cement production reached 4.1 billion metric tons (Btonnes) in 2022, with China responsible for 51.6% of this output. Within the EU27 region, cement production in the same year was around 176 million tonnes (Mtonnes), of which 12.5 Mtonnes of cement and clinker were exported and around 10 Mtonnes were imported, reflecting a demand of approximately 173.5 Mtonnes. This intricate trade balance highlights the complex factors influencing regional production capacities, market demands, and strategic positioning within the EU27.

Reducing emissions from cement production poses a challenge due to the industry's dependence on carbon-containing raw materials and high-temperature requirements (IEA, 2023c), resulting in persistently high historical emission levels (Ana Morgado & Paul Hugues, 2023). Despite the European Union's (EU) Green Deal Industrial Plan introduced in February 2023, aimed at simplifying, expediting, and aligning incentives to bolster the EU's standing as a hub for net-zero industries, specific measures addressing the transition in energy-intensive sectors like cement remain underdeveloped (Ana Morgado & Paul Hugues, 2023).

Accurate assessments of the actual potentials for each technology or measure, along with the associated costs, are crucial for selecting mitigation options and formulating targeted policies for climate mitigation (Kermeli et al., 2016). Long-term energy models are commonly employed for the examination of strategies aimed at reducing emissions and the corresponding investment costs. These models offer a comprehensive perspective of the global energy system, considering various factors including historical energy and material demand, supply sources, technological advancements, socio-economic implications, and environmental impacts to illuminate future scenarios of the energy landscape.

However, Edelenbosch et al. (2017) demonstrated notable differences in long-term energy models concerning the production of global material production including, clinker, cement, and non-metallic minerals, as well as for the energy use and intensity. While existing models provide insights into global energy systems and industrial emissions, they often lack detailed, sector-specific analyses for industries like cement. Notably, many models include cement production within the broader non-metallic minerals sector, encompassing diverse processes with varying characteristics such as glass, lime, brick and tiles. (Edelenbosch et al., 2017). This generalization limits the understanding of specific decarbonization options for the cement industry.

Additionally, Kermeli et al. (2019) highlighted that only a limited number of models possess a module featuring detailed bottom-up information specifically designed for the cement industry. These models typically rely on historical observed correlations between economic activity and material intensity, which constrains a comprehensive analysis under different climate policy scenarios.

1.1 Gap in Literature

Current research highlights the importance of integrating various factors into cement demand forecasting models. Kermeli et al. (2019) modelled the physical demand of cement based on regional indicators of energy and carbon dioxide intensities. They included energy efficiency measures through retrofitting cement plants and reducing the clinker-to-cement ratio to incorporate efficiency improvements in energy demand projections. Similarly, Obrist et al. (2021) integrated improvements in individual process steps in both material and energy substitutions, including cement recycling, and CCS technologies. However, both studies overlook differences in cement end-users and diverse demand contexts.

Xu et al. (2023) included physical drivers of cement demand to improve projections of cement demand. Their study combines the macro characteristics of the cement industry and end-use demand drivers with the strength of cement materials to formulate projections for cement demand in Shandong Province, China. Their model categorizes cement demand into the industrial, construction, and transportation sectors and includes exogenous regional variables such as population, urbanization level, rural and urban per capita building space demand, highway and railway mileage, and industrial investment to determine the demand from the different end-users. Similarly, Uratani & Griffiths (2023) modelled cement demand for African and Asian countries, linking it to population and urbanization growth. However, these studies lack consideration of the economic impact and technological advancements.

Furthermore, Mathiesen et al., (2023) introduced the tool IndustryPLAN, accommodating both bottom-up and top-down modelling of industrial decarbonisation scenarios within the EU27 and the UK. This tool provides a flexible platform for developing future industry energy scenarios based on a range of potential energy efficiency measures, electrification measures, and hydrogen fuel shift measures. IndustryPLAN integrates cement production projections based on the EU Reference Scenario 2020 (European Commission et al., 2021), considering factors such as financial dynamics, technological advancement, socio-economic elements, current policies, and market trends. Additionally, the EU Reference Scenario 2020 (European Commission et al., 2021) includes interconnections between different sectors, such as the one of the construction sector with cement demand. However, cement demand projections within the tool fall under the non-metallic minerals sector and are based on the available data from past activity levels and the average energy intensity per industrial product, which limits the granularity needed for specific decarbonisation strategies.

Despite advancements in cement demand forecasting, there is a critical need for more comprehensive models that integrate sector-specific details, physical drivers of demand, and consider socio-economic and technological impacts, especially within the EU context. Addressing these gaps will enhance strategic planning within the cement industry and support the development of targeted policies for emissions reduction.

1.2 Research Aim

Therefore, this study aims to address these gaps by developing a comprehensive framework for forecasting cement demand that integrates both bottom-up (sector-specific details and physical drivers) and top-down (socio-economic conditions and technological advancements) details. By incorporating these elements, the proposed framework seeks to provide a more accurate and actionable tool for predicting cement demand, thus enabling better strategic planning and supporting the industry’s transition towards sustainable practices. The study focuses specifically on the EU27 region and includes a case study on one EU27 nation to evaluate the framework’s applicability and effectiveness.

Hence, this research aims to answer the following research question:

“Which indicators should be included and how can they be used to model cement demand projections for a more accurate representation of the industry’s energy requirements in explorative decarbonization scenarios of the EU27 region?”

To enable a comprehensive analysis of the research question, the study will answer the following sub-questions:

i. *How did cement supply and demand develop within EU countries and the EU27 region in the period between 2002 and 2022, and what is the correlation with socio-economic trends?*

ii. *How do current long-term energy models that include a specific module for the cement sector forecast demand in their approach?*

iii. *Which factors should be included when forecasting and modelling cement demand in the EU27 region and how are they interconnected?*

iv. *How detailed can the application of the developed framework for forecasting cement demand be in a case study for an EU27 country when looking at easily available data sources?*

1.3 Societal Relevance

The cement industry’s significant contribution to global CO_2 emissions necessitates targeted policies to drive decarbonization and sustainable practices. Accurate forecasting of cement demand is crucial for policymakers to craft effective regulations and incentives. By understanding the detailed dynamics of cement demand and its drivers, policymakers can design more informed policies that promote energy efficiency, support technological advancements, and set realistic emission reduction targets. Furthermore, exploring options to influence cement demand drivers could offer additional avenues for mitigating the industry’s environmental impact.

The cement industry faces increasing pressure to reduce its carbon footprint while meeting the growing global demand. Producers need precise demand forecasts to plan investments, optimize production processes, and adopt new technologies and fuels. A comprehensive understanding of cement demand and its drivers provided valuable insights for cement producers by offering a deeper perspective into both short-term and long-term demand trends. It helps anticipate market shifts, optimize supply chains, and assess the financial implications of adopting various decarbonization strategies. Additionally, aligning their strategies with evolving market conditions and regulatory requirements, enhances their competitiveness and sustainability.

1.4 Chapter Outline

To navigate the report effectively, the following guide outlines the contents and structure of each chapter.

Chapter 2 focuses on analysing historical trends of indicators that influence cement consumption in the EU27 region and at the country level, examining how these variables impact cement demand. Chapter 3 evaluates existing long-term energy models that include a cement sector module, supplemented by an expert interview to identify key forecasting methodologies, practical considerations, and industry perspectives on cement demand modelling. In Chapter 4, a conceptual framework for forecasting cement demand at the country level within the EU27 is developed, highlighting key influencing factors and their interrelationships. Chapter 5 validates this framework through a case study in the Netherlands, assessing its detail and accuracy in projecting cement demand. Chapter 6 discusses the theoretical implications and limitations of the study, proposing avenues for future research. Finally, Chapter 7 concludes the research.

2 Cement Supply and Demand

Understanding the nuances of cement production and its applications is crucial for grasping the broader dynamics of the cement industry. Variations in clinker content contribute to the complexity of cement supply and demand, while the interplay between construction activity and socio-economic factors highlights the importance of a holistic approach to understanding cement market dynamics. Therefore, this chapter explores historical trends of cement supply, cement end-user, and socio-economic indicators on a country level of the EU27 region, and the EU27 as a whole. The aim is to identify insights into how changes in these variables influence cement demand, highlighting key considerations for cement demand modelling, and address research sub-question i:

"*How did cement supply and demand develop within EU countries and the EU27 region in the period between 2002 and 2022, and what is the correlation with socio-economic trends?"*

This chapter begins with a discussion of cement production and its applications in Section 2.1. Section 2.2 describes the methodology used in the chapter. The results of the trend and correlation analyses are presented in Section 2.3 and Section 2.4, respectively. Finally, Section 2.5 reviews and draws conclusions from the findings discussed throughout the chapter.

2.1 Cement Production and Applications

The process of cement production involves the meticulous blending and grinding of raw materials, typically limestone, and clay, followed by heating, calcination, and sintering in a kiln. This results in the formation of clinker, which once finely ground, is a fundamental product in the production of cement. After clinker is produced, cement grinding takes place, where clinker is mixed with gypsum to form cement. The share of clinker in cement production, often referred to as the clinker-to-cement ratio, plays a crucial role when modelling cement production and the related energy use as it is the most energy-intensive part of cement manufacturing as well as a significant source of CO_2 emissions of the total emissions from cement manufacturing. According to the IEA (2023), the thermal energy intensity for producing one ton of clinker is approximately 3.6 GJ. This energy is primarily derived from burning fossil fuels such as coal, natural gas, or oil.

The clinker-to-cement ratio varies between cement plants. In the EU27 region, the current average clinker-to-cement ratio is estimated at 74% across all cement types (European Cement Association, 2023a). Reducing the clinker content in cement production is essential for reducing CO_2 emissions, making the exploration of alternative materials and innovative technologies crucial for achieving a lower carbon footprint (Barcelo et al., 2014). To partially substitute clinker and reduce CO_2 emissions, cement can be blended with Supplementary Cementitious Materials (SCMs) such as slag, fly ash, limestone, or other materials. However, the availability of SCMs like fly ash and slag relies on the development of other industries such as the coal, iron, and steel industries, underscoring a symbiotic relationship between the decarbonisation of the cement industry with other industries (Duchesne, 2021). Advancements in material science are enabling the exploration of Alternative Supplementary Cementitious Materials (ASCMs). ASCMs include silica from silicon metal manufacturing and blast furnace slag from iron ore reduction, which can either replace or enhance the role of SCMs in cement production (Duchesne, 2021).

Depending on the composition of cement production, different cement types are produced and categorized into various classes. The European cement standard EN 197-1 defines 27 distinct types of cement and their component materials, grouping them into the following specific categories (European Committee for Standardization, 2011):

- CEM I Portland cement (>95% clinker)
- CEM II Portland-composite cement (65-94% clinker)
- CEM III Blast furnace cement (5-64% clinker)
- CEM IV Pozzolanic cement (45-89% clinker)
- CEM V Composite cement (20-64% clinker)

The difference in clinker content influences the range of applications for which each cement type is suited (European Cement Association, 2023a). CEM I, with its high clinker content, offers excellent strength and is often used for structural applications requiring high durability and load-bearing capacity (CEMEX UK, 2021). However, its higher carbon footprint has made it less attractive in recent years.

In contrast, CEM II and CEM III contain a lower proportion of clinker and incorporate SCMs, which reduce the carbon footprint of cement production but also enhance certain properties. CEM II contains limestone or fly ash, is versatile and suitable for general construction purposes (CEMEX UK, 2021). It is commonly used in non-structural applications such as pavements and buildings with less stringent durability requirements. Furthermore, CEM III has a higher blast furnace slag content and excels in applications requiring high resistance to aggressive environments, such as marine structures and concrete exposed to severe conditions (CEMEX UK, 2021).

CEM IV and CEM V represent further advancements in sustainable cement technology. CEM IV incorporates pozzolanic materials, such as volcanic ash or natural pozzolans, which enhance the cement’s performance while reducing its clinker content (CEMEX UK, 2021). CEM V combines both pozzolanic and blast furnace slag materials, offering even greater sustainability and versatility (CEMEX UK, 2021). Its composition allows for excellent durability and resistance to environmental stressors, making it suitable for a wide range of demanding applications, from industrial buildings to large-scale infrastructure projects (CEMEX UK, 2021). However, the adoption of CEM IV and CEM V in the EU remains limited (Xavier & Oliveira, 2021).

The main activity of cement is the production of two types of concrete: ready-mix-concrete and prefabricated concrete. Ready-mix concrete is produced at a ready-mix batch plant and transported to construction sites (European Cement Association, 2023a). This type of concrete is manufactured under controlled conditions, ensuring uniformity and quality. The primary advantage of ready-mix concrete is its convenience and efficiency, as it is delivered ready to use, saving time and labour on-site (Al Manaratain, 2019). Ready-mix concrete is widely used in large-scale construction projects, including highways, bridges, and buildings, due to its consistent quality and performance (Al Manaratain, 2019).

Prefabricated concrete, on the other hand, is cast in reusable moulds and in a controlled environment and then distributed to construction sites. This method allows for precise control over the concrete’s composition and curing conditions, resulting in high-quality, durable products. Prefabricated concrete elements, such as beams, columns, and panels can be lifted into place instantly upon arrival at the construction site (European Cement Association, 2023a).

This reduces construction time and labour costs and enhances the overall project efficiency (Heincke et al., 2019). Prefabricated concrete is mainly used in modular construction, where speed and precision are critical, such as in the construction of residential buildings, commercial complexes, and industrial structures (Heincke et al., 2019).

In addition to these primary uses, cement is also sold to various other end-users through retailers and wholesalers (European Cement Association, 2023a). Cement in bags is commonly used for mortar and small concrete batches by contractors producing their own concrete and individual consumers (European Cement Association, 2023a). Bagged cement is especially useful for smaller-scale projects, including household renovations, landscaping, and minor repair works (European Cement Association, 2023a). Contractors producing their own concrete and mortars for large construction projects also rely heavily on bulk cement supplies (European Cement Association, 2023a). Contractors often mix cement on-site to meet specific project requirements, ensuring flexibility and control over the construction process (European Cement Association, 2023a).

Concrete is mainly used in the construction sector, establishing a close link between construction activity and cement demand (Kermeli et al., 2019). For instance, the growth in residential construction could lead to an increased demand for cement due to higher volume of concrete needed for new housing developments, renovations, and repairs (IEA, 2021). This increased demand for cement can translate into expanded production at cement plants or cement imports and potentially increased prices in the market as suppliers adjust to meet the higher demand requirements (Heincke et al., 2023). Conversely, the slower growth in infrastructure and non-residential buildings might indicate a period of stabilization or reduced investment in these sectors, potentially leading to a more balanced or even decreased demand for cement in these end-users (Heincke et al., 2023).

2.2 Methodology

Table 1 presents the indicators explored in this study. The selection of indicators in this analysis focused on capturing factors that shape and influence cement consumption across various sectors. This included cement supply and demand, cement end-users, and socio-economic indicators. The explored indicators represent potential drivers of cement demand from both the direct use in construction and the overall socio-economic climate that influences construction activity and the cement industry.

Table 1: Cement supply, demand, and socio-economic indicators used to analyse the factors influencing cement consumption.

Indicator	Disaggregation	Period Covered	**Unit**	Source
Cement Supply Indicators				
Clinker production	-	2002-2021	tonnes	(UNFCCC, 2023)
Cement production	-	2002-2021	tonnes	Calculated
Imports and Exports of cement	-	2002-2022	tonnes	(Eurostat, 2024c)
Cement Demand	-	2002-2021	tonnes	Calculated
Socio-economic indicators				
Population	-	2002-2022	inhabitants	(Eurostat, 2024f)

GDP	-	2002-2022	€ in 2010 prices	(Eurostat, 2024d)
Cement end-user indicators				
Building Permits	• Total Buildings • Residential • Non-residential	2005-2022	m^2	(Eurostat, 2024b)
Gross Value added in Construction			€ in 2010 prices	(Eurostat, 2024e)
Production in Construction	• Buildings • Civil engineering works • Other specialized construction activities	2002-2022	Annual % change	(Eurostat, 2024g)
Infrastructure stock	• Road • Railways • Airport runways	2002-2022	km^2	(Eurostat, 2024i) (Eurostat, 2024h) (Eurostat, 2024a)

The total amount of cement utilized within each country or otherwise, the domestic apparent cement demand was calculated in this study by aggregating the domestic cement production and net imports of cement, encompassing both intra-EU trade and extra-EU trade. Since data for domestic cement production for EU27 countries was not available online, clinker production data was gathered and multiplied by the current average clinker-to-cement ratio over all cement types for the EU27, to estimate domestic production. The clinker-to-cement ratio in the analysis was assumed to be 73.7% in accordance with the European Cement Association (2024) estimation. It is important to note that this is an average value, and individual EU countries may have higher or lower clinker-to-cement ratios. This can potentially lead to an underrepresentation of cement demand in countries with a higher clinker-to-cement ratio and an overrepresentation in countries with a lower ratio.

The Building Permits Index (BPI) is measured in m^2 and reflects the useful floor area for which building permits are issued. BPI encompasses all types of residential buildings including one dwelling, two or more dwellings, and residences for communities. One-dwelling units include detached, semi-detached, and terraced houses. Two-or-more dwellings include buildings with multiple apartments or flats, while residential communities include communal living spaces such as dormitories, and retirement houses. Non-residential building permits include offices, hotels, shops, warehouses, industrial buildings, schools, and hospitals.

A building permit serves as the final administrative approval for commencing a particular construction project, while the extent of work not necessitating a permit is usually restricted. Consequently, the progression of the building permits index is roughly equivalent to that of the actual construction work (European Commission, 2024a). However, variations in the time gap between permit issuance and construction start and end time can lead to discrepancies between BPI and the actual level of construction activity. Factors like construction type and size (that influence the project completion time) and economic conditions (that could provoke delays due to financial issues) can influence this time gap. These discrepancies can manifest in two ways. Unused permits may inflate the indicator, potentially overestimating future building activity (European Commission, 2024a). This can occur if permits expire before construction begins, or if economic downturns cause project delays. Conversely, construction projects that span over a year may not require a new permit for continuation and can lead to the BPI underestimating future building construction activity, particularly for larger or more complex projects (European Commission, 2024a). Additionally, the BPI does not adjust for the withdrawn of permits, potentially resulting in double counting if a project restarts with a new permit after the initial permit expires. Moreover, the BPI might include all types of construction activities since there is no specification of whether the permit concerns a new construction project or a different construction activity.

The index Gross Value Added (GVA) in construction reflects the net contribution of the construction industry to the GDP of a country (European Commission, 2019). It encompasses the value added to the economy by all construction activities, including the construction and maintenance of residential and non-residential buildings, civil engineering works including railways, roads, bridges, and airport runways, and other specialized tasks in the construction sector like enterprises involved with the installation, completion, and finishing activities. While the construction of buildings and civil engineering works require substantial quantities of cement, other specialized tasks may not directly impact cement demand. For instance, interior finishes, electrical works, and plumbing installations rely more on specialized materials rather than cement. Additionally, GVA is a monetary measure and does not directly track the specific materials used in construction activities. Instead, GVA captures the total economic contribution of various stakeholders involved in construction processes, encompassing labour, equipment, and materials (European Commission, 2019).

The production index for construction, measures monthly and annual fluctuations in the volume of construction output, after accounting for price changes (European Commission, 2024b). This index disaggregates buildings and civil engineering works, which is not provided by the rest of the construction indicators, enabling the exploration of the correlation between each sector with cement demand. While for buildings the BPI already serves this purpose, civil engineering works can be treated as a separate sector when using the production index. However, the index does not enable a comparison of the share of each sector in total construction production, since the available data indicate the annual rate change and not the total production in each year.

The infrastructure stock indicator offers a snapshot of the existing infrastructure within a county (European Commission, 2023b). These datasets further disaggregated by specific types of civil engineering works, allow for a more nuanced understanding of how specific types of infrastructure projects correlate with cement demand. However, this focus on specific types of infrastructure may underestimate the overall correlation of the civil engineering sector with cement demand. This is because the cumulative impact of all kinds of infrastructure projects will have a stronger explanatory power rather than a specific type of infrastructure project.

Furthermore, to explore any potential correlation between cement demand and the explored indicators, the correlation coefficient (r) and the coefficient of determination (r^2) were computed and compared. The correlation coefficient measures the strength and direction of the linear relationship between two variables in a time horizon and ranges from -1 to 1. A positive value of r indicates a positive correlation, where an increase in one variable tends to increase the other, while a negative value denotes the opposite. Values near zero suggest minimal or no linear relationship between the variables. The coefficient of determination complements the correlation coefficient by directly quantifying the proportion of the variability in one variable that is predictable from the other variable, providing a more comprehensive understanding of the relationship between the variables. It ranges from 0 to 1, with an r^2 value of 1 indicating a perfect linear relationship between the variables, meaning that all the variability in one variable can be precisely explained or anticipated by the other variable.

2.3 Trend Analysis

2.3.1 Socio-Economic Indicators

Figure 1 presents the evolution of population and GDP in the EU27 as a whole for the period between 2002 and 2022. The total population of the EU27 as a whole has increased by approximately 15 million inhabitants throughout the studied period, reaching a population of approximately 447 million. The only year to showcase a decrease in population compared to the previous year for the EU27 in the studied period was 2011, with most countries experiencing a slow but consistent population growth over the two-decade period.

On a country level, Bulgaria, Romania, Lithuania, Latvia, and Croatia are amongst the countries that experienced decreasing population during the studied period. Germany’s population decreased by 1.5 million in 2011 compared to the previous year but saw a subsequent increasing trend, exceeding the population of 2010 by 2016 and growing even further in the following years. Furthermore, France displays greater growth in population throughout the studied period, increasing by around 6.33 million from 2002 to 2022. According to the European Commission (2024c), in 2022 only 6 EU Member States including Ireland, Cyprus, Luxembourg, Sweden, France, and Malta, experienced a positive natural increase of population. In the remaining Member States, deaths outnumber births and a total of 26 Member States exhibit positive rates of net migration, which was the driver of population growth in 2022 for 14 Member States.

The GDP of EU27 has increased by approximately 31% from 2002 to 2022. Despite a significant downturn in 2009 due to the global economic crisis, the EU experienced subsequent recovery. In 2020, there was a decrease of 6% compared to the previous year, potentially exacerbated by the COVID-19 pandemic, which surpassed the 4% decrease observed in the later year of the economic recession. On a country level, most Member States demonstrated consistent growth in GDP, with Germany maintaining the highest value among the 27 Member States throughout the studied period, followed by France, Italy, and Spain respectively. Greece notably struggled to recover fully from the economic recession, as it remained the only country unable to reach its pre-recession GDP levels.

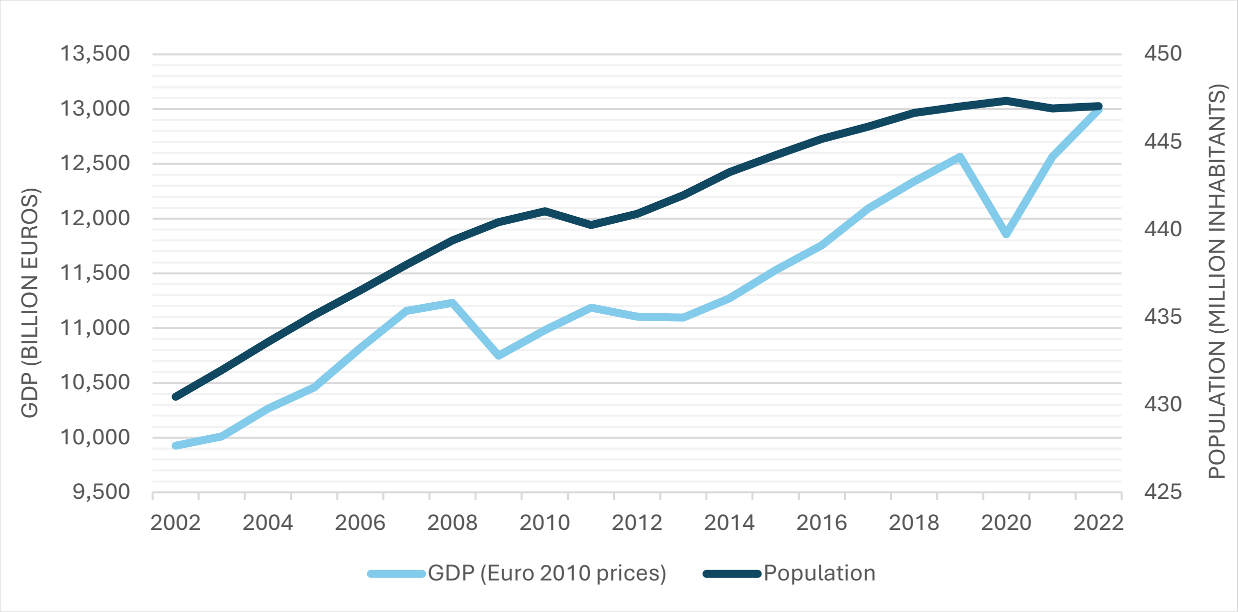

Figure 1: Population (in million inhabitants) and GDP (in billion Euros) in the EU27 between the period 2002 to 2022, as retrieved by Eurostat (2024f), and Eurostat (2024d).

2.3.2 Cement Supply Indicators

Figure 2 shows cement production in the EU 27 per country and as a whole from 2002 to 2021. Cement production in the EU27 steadily increased from 2002 until reaching a peak in 2007. However, with the onset of the global economic recession in 2008, production began to decline in most Member States. While countries like Italy, Spain, and Greece continue to recover from the recession's impacts on cement production, others such as Germany, Austria, the Netherlands, Sweden, and Luxemburg have demonstrated greater resilience, maintaining relatively stable production levels despite fluctuations.

Notably, Germany emerged as the largest cement producer in the EU27 region in 2011, surpassing Italy and Spain, which were the leading European cement producers prior to the economic recession. Poland stands out as the only country consistently increasing its cement production levels over the studied period, Meanwhile, Malta remains an exception with zero production. Additionally, the Netherlands experienced a significant decline in cement production, dropping by approximately 97% in 2019 compared to the previous year, and followed by zero production in 2020 and 2021. However, this apparent decline is due to a data error in the study's calculation methods. The actual reason for the zero production is the cessation of domestic clinker production with the closure of the country's sole clinker production facility in 2020 (Xavier & Oliveira, 2021).

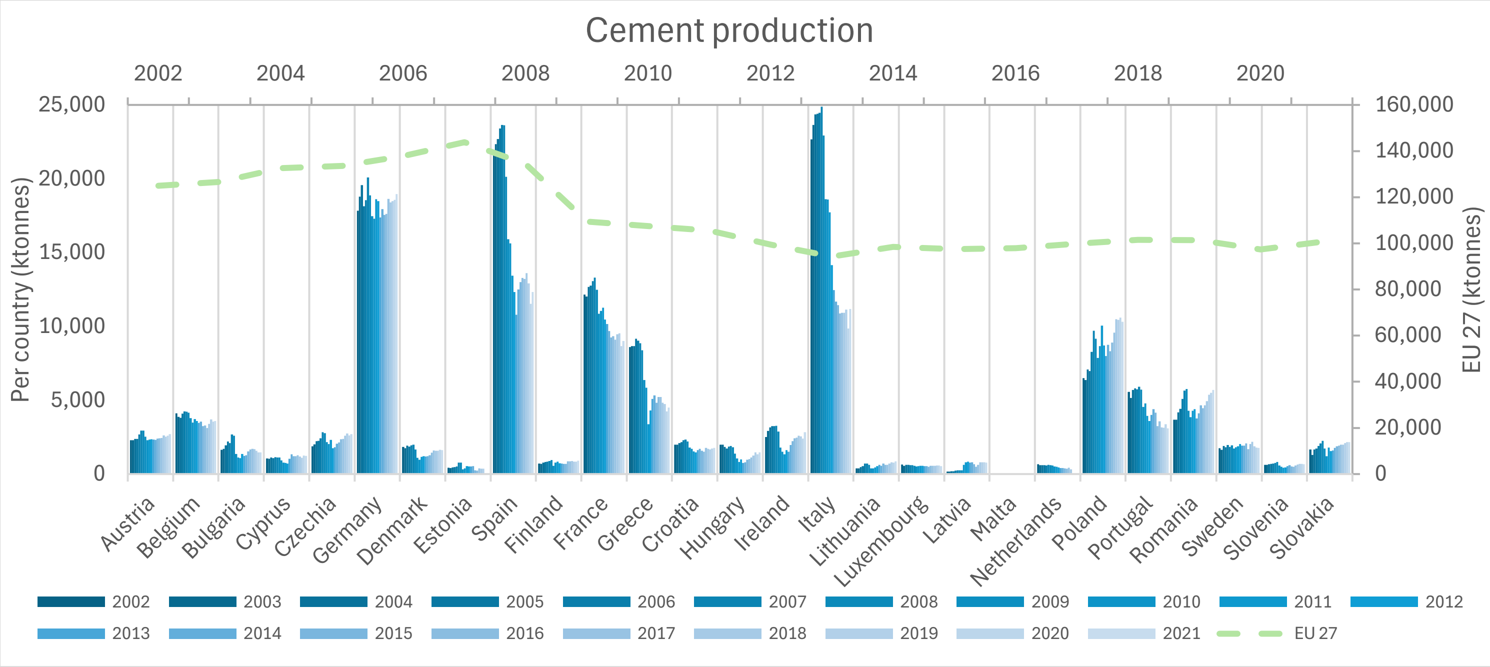

Figure 2: Cement production (in ktonnes) for the EU27 as a whole (righthand y-axis) and per country (lefthand y-axis) between 2002 and 2021, as calculated in this study.

Furthermore, Figure 3 illustrates net cement imports for EU27 Member States, encompassing both intra-EU and extra-EU trade from 2002 and 2022. It presents the balance between cement imports and exports, with aggregate data for the entire EU27 also included. Similar to cement production, EU27 cement imports experienced a period of growth from 2002 to 2007, peaking that year. A subsequent 43% decline occurred between 2007 and 2009, followed by a gradual decline until 2012. Imports stabilized until 2017, then slightly increased to 2021, with a steady level in 2022 compared to 2021.

Conversely, EU27 cement exports have been on the rise since 2002, reaching a peak in 2014 before gradually declining until 2022. The region shifted from a net importer to a net exporter post-2008 economic crisis. However, only 6 of the 27 Member States transitioned from net importers to net exporters. These include Czechia, Italy, Latvia, Portugal, Slovenia, and Spain. On the contrary, Romania, Poland, and Estonia experienced the opposite transition, while Bulgaria's status fluctuated, transitioning from a net exporter to a net importer and back again to a net exporter. Other countries maintained consistent import or export surpluses, with varying impacts. Countries exporting cement include Belgium, Cyprus, Denmark, Germany, Greece, Croatia, Ireland, Lithuania, Luxembourg, Portugal, and Slovakia. Meanwhile, Austria, Finland, France, Hungary, Malta, and the Netherlands are among the countries importing cement.

The cement's industry sustainability challenges are reshaping the supply dynamics of the region. Between 2016 and 2022, EU27 cement and clinker imports surged by approximately 300%, while exports fell by approximately 52% in the same period (European Cement Association, 2023c). Notably, Spain, Greece, Belgium, and Italy experienced significant import growth of 1423%, 954%, 848%, and 691%, respectively, between 2016 and 2022 (European Cement Association, 2023b).

Doutres (2022), delved into the intricate dynamics of cement trading within the Mediterranean region, highlighting the impact of economic crises, migration flows, political instability, and the impact of the COVID-19 pandemic. The European cement industry is increasingly focused on environmental sustainability, with producers compelled to adopt alternative fuels and SCMs to reduce carbon emissions (Doutres, 2022). The introduction of the EU ETS and increased CO_2 costs have added a layer of complexity, particularly for Southern European producers, intensifying the pressure on them, and possibly forcing an increase in the price of clinker (Doutres, 2022). Southern European cement producers, among other Europeans, face challenges in adapting to green and efficient cement supply chain and are now navigating international markets with distinct considerations compared to their counterparts, reflecting a paradigm shift driven by regulatory aspects (Doutres, 2022).

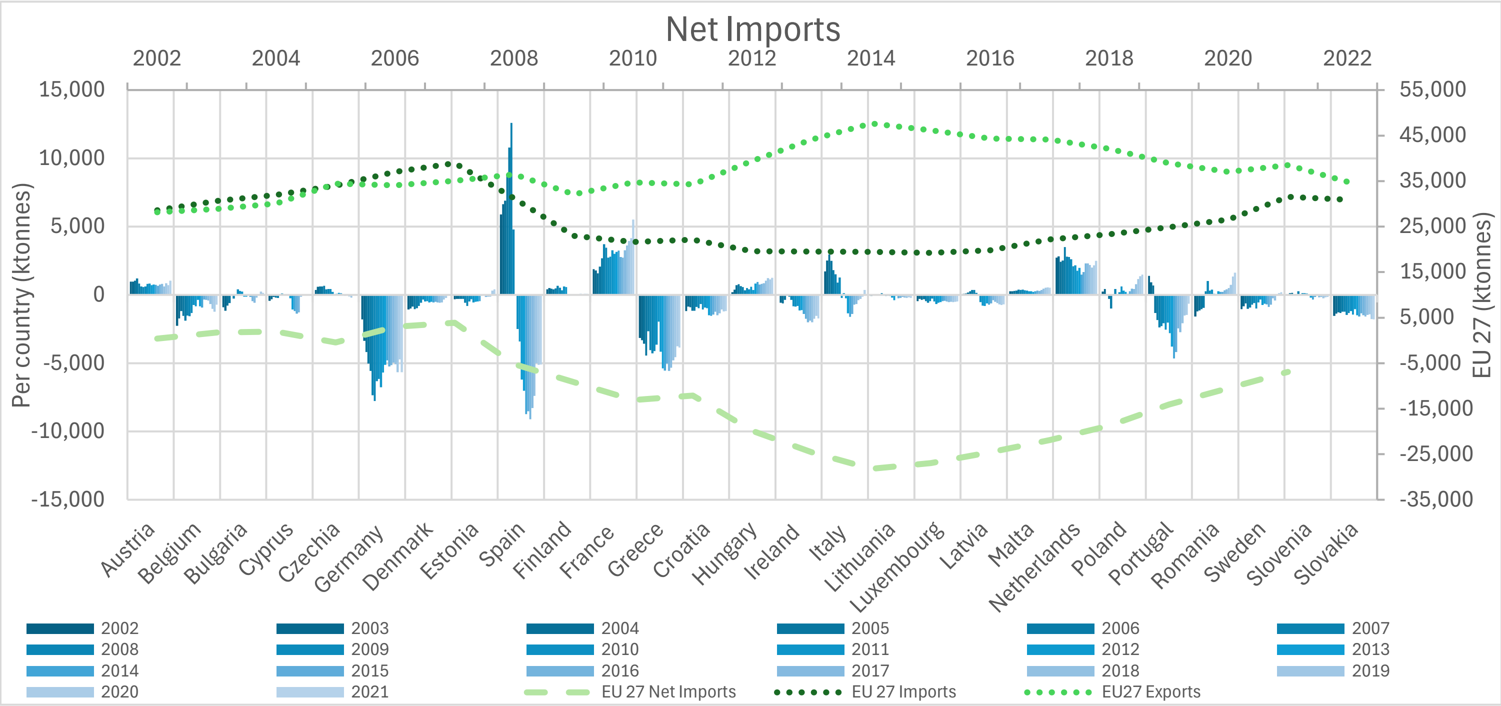

Figure 3: Net Imports (in ktonnes) per country (lefthand y-axis) and Net Imports, Imports, and Exports of the EU27 as a whole (righthand y-axis) for the period between 2002 and 2022, as retrieved by Eurostat (2024c).

2.3.3 Cement End-User Indicators

Figure 4 illustrates the GVA in construction in Euro 2010 prices for the EU27 region and individual countries from 2002 to 2022. Construction GVA in EU27 reached a peak in 2008 after a period of slow growth since 2002, followed by a decline until 2014. Construction GVA subsequently recovered until experiencing a downturn in 2020, likely due to the COVID-19 pandemic. Greece and Spain suffered the most severe declines in construction GVA. In 2021, construction GVA in Greece and Spain were 70% and 46% lower, respectively, compared to their 2007 peaks. While Spain's GDP recovered after the economic recession, its construction GVA did not. The same pattern is observed in France and Italy. In contrasts, Belgum, Poland, and Sweden demonstrated consistent growth throughout the studied period, even during the economic crisis.

Within the Euroconstruct area in 2022, there was a 3% increase in the value added from construction compared to the previous year (EUROCONSTRUCT, 2023). Total buildings saw a growth of 3.6%, with residential buildings growing at a rate of 4.6%, and non-residential buildings and infrastructure growing at a rate of 1.9% and 0.6% respectively (European Cement Association, 2023b).

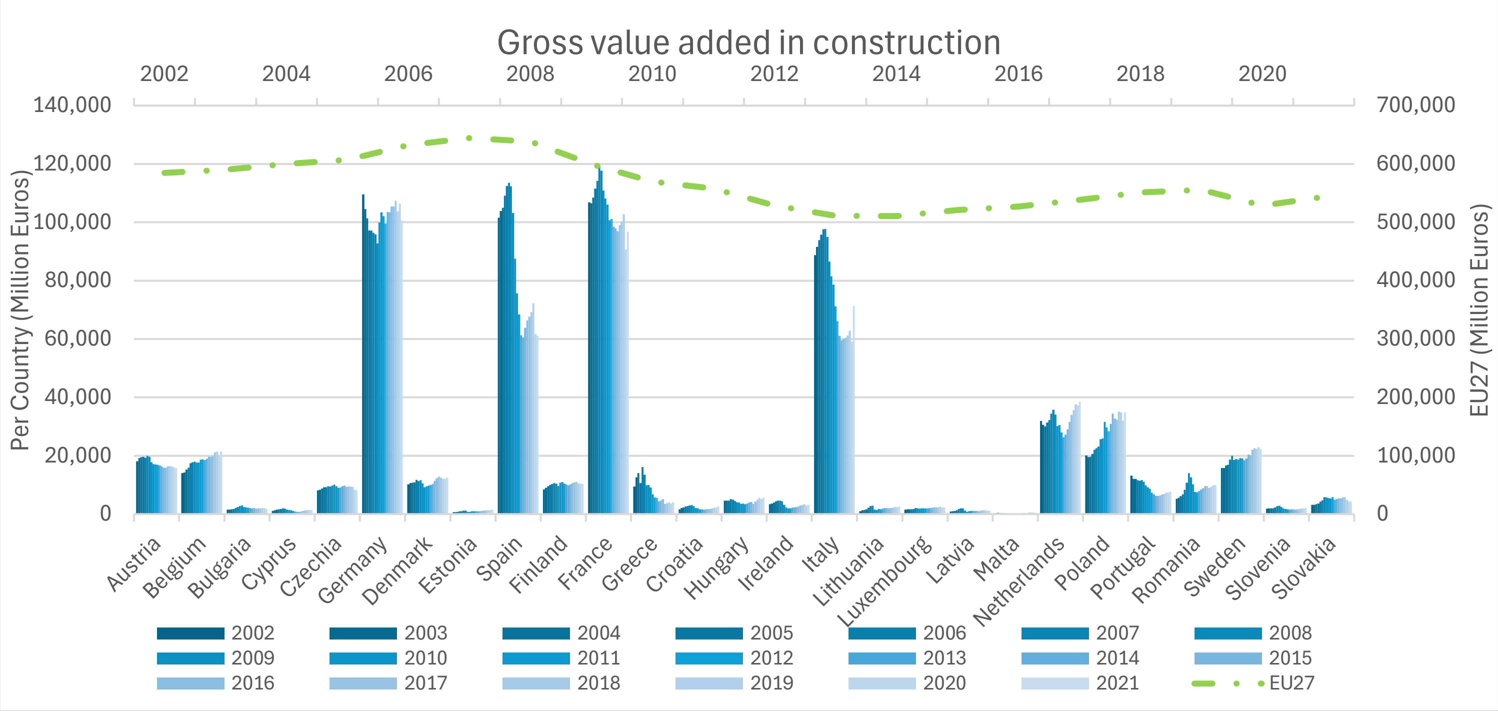

Figure 4: Gross value added in construction in Euros 2010 prices for the whole EU27 (righthand y-axis) and per country (lefthand y-axis) for the period between 2002 and 2022, as retrieved by Eurostat (2024e).

Figure 5 illustrates the annual percentage change of production in the construction of buildings and civil engineering works from 2002 to 2023 for the EU27 region. During this period, both types of building construction and civil engineering works experienced alternating phases of growth and degrowth. From 2002 to 2007, there was a growth phase for both building construction and civil engineering works. The economic recession in 2008 led to a subsequent period of degrowth for both sectors. Notably, 2011 saw a significant increase, followed by a substantial decrease in the following year. Starting from 2014, another period of growth began in the EU27. However, in 2020, the outbreak of the COVID-19 pandemic resulted in a year of decline, with a decrease of 4.8% in building construction and a 3.7% decrease in civil engineering works. In 2021, building construction increased by 6.2% and civil engineering works by 2.8%, with further increases continuing into 2022.

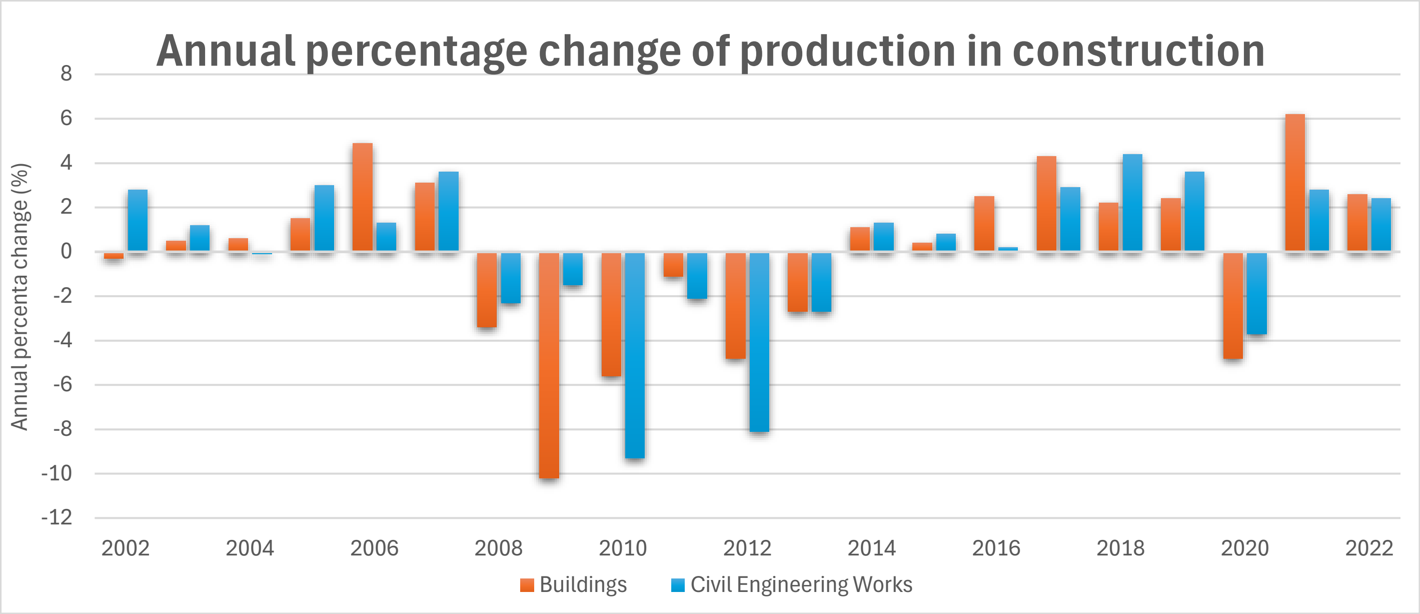

Figure 5: Annual percentage change of production in construction of buildings civil engineering works from 2002 to 2023 for the EU27 region, as retrieved by Eurostat, (2024g).

Furthermore, Figure 6 shows the evolution of the BPI for the EU27 region and individual countries from 2005 to 2022. For the EU27, building permits peaked in 2006, with periods of decline caused by the economic recession in 2008 and the COVID-19 pandemic in 2020. Spain and Greece experienced the most severe reductions, with their indices dropping by 82% and 76%, respectively, in 2021 compared to their peak year. In the pre-crisis period, Spain and Greece encountered a housing bubble characterized by inflated property values and excessive development (European Commission, 2022). This led to a downturn in demand for new residential buildings when property prices collapsed. The government responded with measures like stricter lending criteria to stabilize the real estate market (Sprecher et al., 2022). However, economic uncertainty and reduced consumer confidence further decreased both residential and non-residential building permits, resulting in halted projects, insolvency of construction firms, and a surge in unemployment within the sector for both countries (Sprecher et al., 2022). In contrast, Belgium, Poland, and Germany are the only countries that recovered from the effects of the economic recession, surpassing their pre-crisis levels. Austria is unique in demonstrating resilience to the economic recession, maintaining a growth trend throughout the studied period.

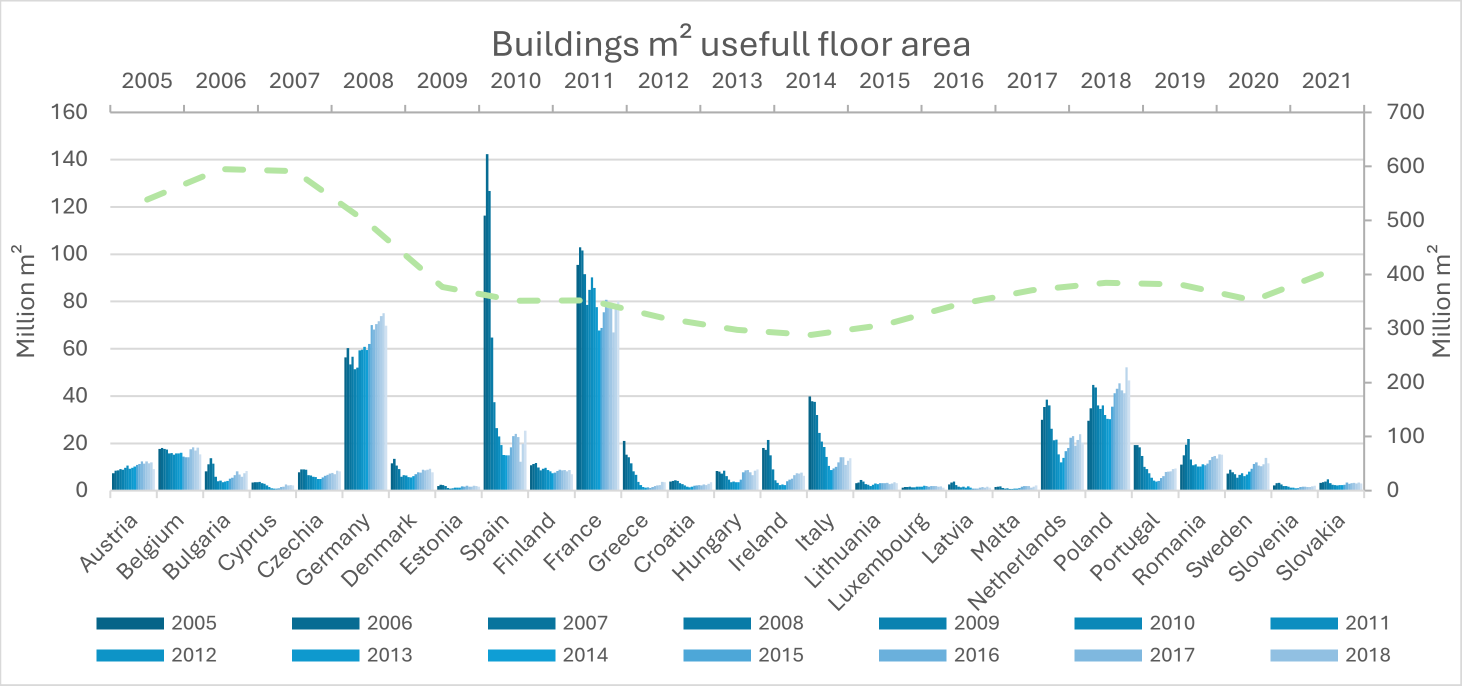

Figure 6: Building Permits index, useful floor area (in million m²) for the EU27 as a whole and per country for the period between 2005 and 2022, as retrieved by Eurostat (2024b).

2.3.4 Cement Apparent Consumption

Figure 7 depicts the apparent cement consumption of the EU27, representing the total amount of cement utilized within each country, aggregating domestic cement production and net imports. Cement demand in the EU27 as a whole peaked in 2007 following a period of steady growth, aside from a decline in 2005. Subsequently, demand declined from 2008 to 2013 but has been on the rise since, except from 2020 likely due to the spread of the COVID-19 pandemic.

On a country level, Spain experienced the most significant reduction in cement demand. From 2007 to 2009, Spain experienced a decrease of approximately 20,000 ktonnes of cement demand, constituting around 43% of the total decrease in EU27 during that time. Italy, France, and Greece followed Spain as the most impacted countries by the economic recession in terms of cement demand, with their demand declining by approximately 6,500, 3,400, and 2,500 ktonnes, respectively, from 2007 to 2009. France appears to have increased cement imports in the later years to meet its demand despite a reduction in domestic cement production. Conversely, Spain and Italy have transitioned to net exporters despite their decreasing production levels, resulting in a significant decrease of cement demand over the studied period. Additionally, Denmark, Poland, Romania, and Sweden are observed to increase their cement demand in the latter years of the studied period.

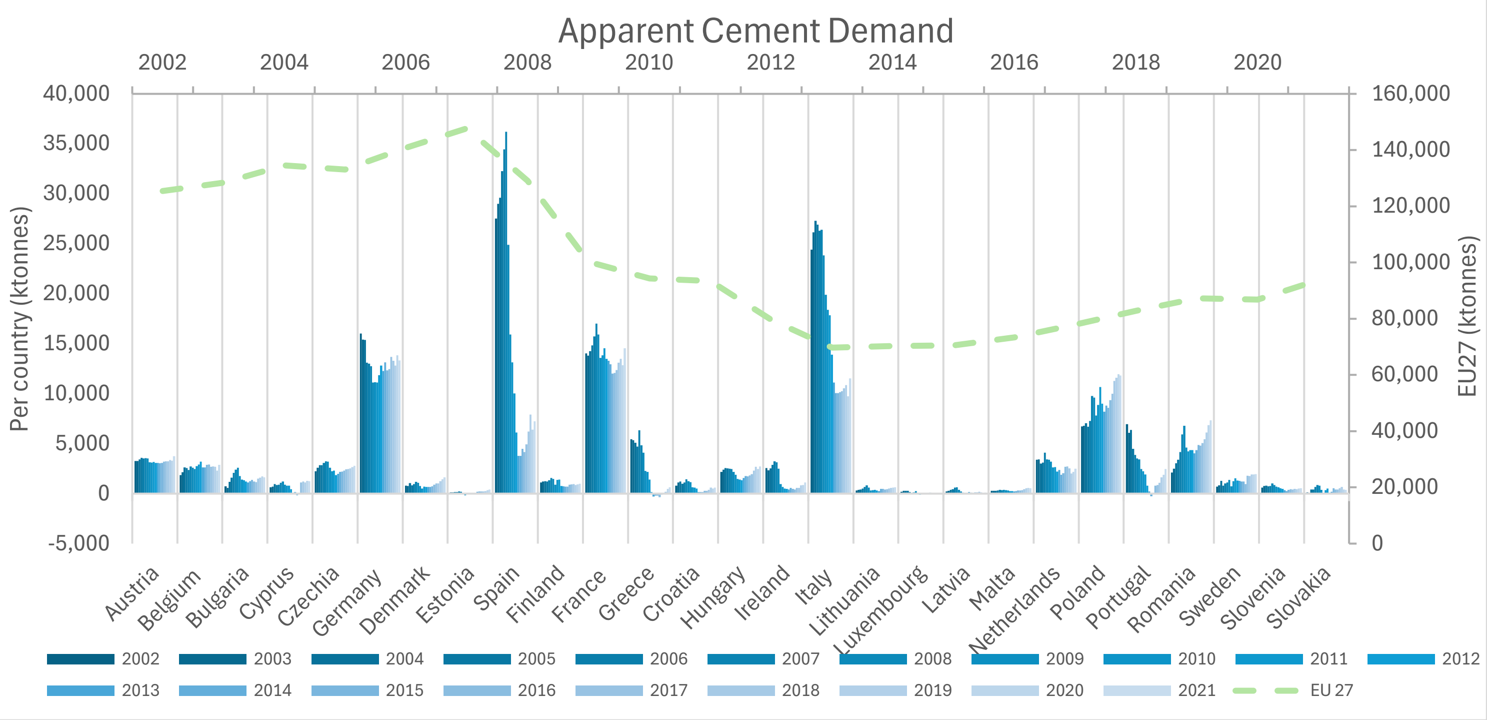

Figure 7: Cement demand (in ktonnes) for the EU27 as a whole and per country from 2002 to 2021, as calculated in this study.

2.4 Correlation Analysis

Figure 8 illustrates the coefficient of determination value for the average of the 27 EU Member States and the EU27 as a whole, between cement demand and the explored indices.

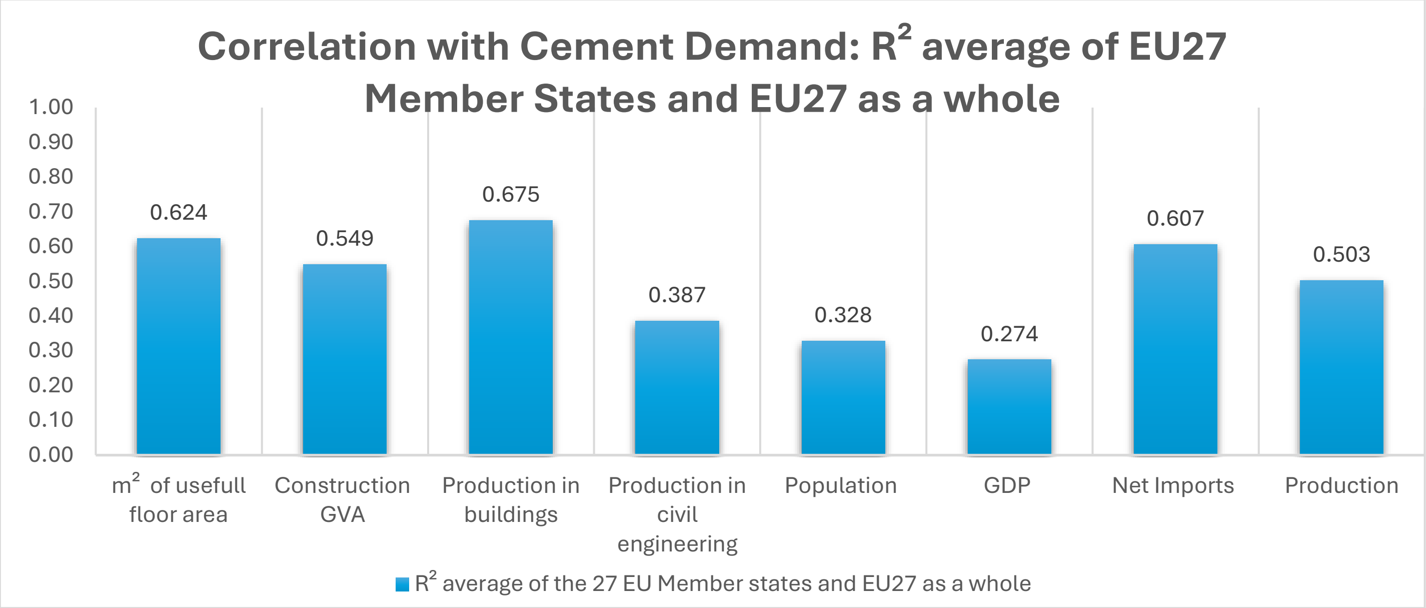

Figure 8: Correlation analysis of cement demand in EU27 Member States with key drivers of cement demand, as calculated in this study.

2.4.1 Socio-Economic Indicators

Growing populations often lead to increased urbanization, infrastructure development, and housing construction, and therefore increasing demand for cement (Xu et al., 2023; Uratani & Griffiths, 2023). However, despite the increasing population across the EU27 and most of its Member States from 2002 to 2022, the correlation between population and cement demand appears weak, indicating an intricate relationship. The correlation coefficient suggests that most countries demonstrating an r value closer to 1 exhibit a negative correlation between population and cement demand, implying that when population was increasing in those countries, cement demand was decreasing, and vice versa.

However, this may be attributed to the fact that while the population in those countries was increasing, cement demand experienced periods of decline due to other driving factors such as economic availability. For instance, the economic recession in 2008 caused 7 years of declining cement demand in the EU27, while population growth remained relatively unaffected. Therefore, while population growth can influence cement demand, various other factors affect demand that may have a stronger impact.

Furthermore, despite exhibiting the weakest correlation among the indicators explored, the relationship between GDP and cement demand demonstrates complexity. For instance, the economic recession significantly impacted the construction sector, leading to substantial shifts in cement production, demand, and trading markets. However, while the construction and cement industries endured prolonged effects from the recession and have yet to return to pre-crisis levels, GDP experienced only a single year of significant decrease during this period. This suggests that sectors beyond cement and construction were the primary drivers of GDP growth in EU27. While the economy has an influential impact on cement demand and can cause disruptions to the cement industry, the influence of other factors unrelated to cement demand on GDP development implies that the correlation between GDP and cement demand is indirect and influenced by a multitude of external factors.

2.4.2 Cement End-User Indicators

Cement demand demonstrates the strongest correlation with annual changes of production in buildings and the BPI out of the correlations explored, with an average r^2 value for the EU27 estimated at 0.66 and 0.61 respectively. While both indicators consider buildings as the only end-users of cement demand, these indicators demonstrated the strongest correlation with demand, suggesting that buildings maintain a higher share in cement demand compared to the rest of cement end-users.

On a country level, the r^2 values for the BPI and cement demand vary considerably. For example, 9 of the 27 countries explored demonstrated an r^2 value ranging between 0.8 and 0.96, while 8 countries ranged between 0.5 and 0.79. Out of the remaining 10 countries, 8 of them spanned from 0.25 to 0.49, while Belgium and Austria demonstrated the lowest r^2 values estimated at 0.14 and 0.02 respectively. This variation across countries likely reflects the influence of regional characteristics that shape the construction industry in a country.

One key factor is the time lag between issuing a building permit and actual cement demand. Unlike the BPI, which is a one-time event, cement demand unfolds over time as construction projects progress. This time lag depends on various project-specific details, such as project complexity, size, and financing arrangements (Lafhaj et al., 2024). Additionally, global and regional economic conditions can influence the pace of construction activity, further impacting the timing of cement demand relative to permit issuance (Alaloul et al., 2022). Therefore, building permits could be a reliable indicator for short-term forecasting, while also providing insights into historical trends in cement consumption.

Moreover, the correlation analysis revealed a moderate correlation between construction GVA and cement demand across the EU27 with an average r^2 value of 0.54. Interestingly, the r^2 values exhibited less variation on a country level than the BPI. Eleven out of the 27 EU countries demonstrated r^2 values ranging from 0.5 to 0.79, while 7 countries exceeded 0.8. Similarly to the BPI, the variations on a country level of correlation between construction GVA and cement demand are driven by regional characteristics.

Furthermore, annual changes in the production of civil engineering works and total road development demonstrated the weakest correlation with cement demand, estimated at 0.37 and 0.26 correspondingly. Variations in the annual change of civil engineering projects correlated less with the development of cement demand during the studied period and countries compared to the production in buildings, despite showing similar trends in their annual development. This suggests that building construction activities play more significant role in driving cement demand than civil engineering works.

2.4.3 Cement Supply Indicators

The correlation between cement demand and net imports/production varies among different nations due to the regional characteristics of their cement industry. Countries relying on imported cement to meet their demand, tend to show a stronger correlation between demand and net imports but a weaker correlation between demand and production. Conversely, countries with an exporting market for cement, producing more cement than they demand, exhibit opposite results. Countries experiencing shifts in their cement industry, including changes in production and trade dynamics, tend to exhibit a strong correlation between demand and both production and net imports. Overall, changes in demand had a stronger explanatory power for changes in net imports compared to variations in production for the EU27. This suggest that the EU27's cement industry is likely more reliant on domestic demand to shape its import and production decisions.

2.5 Discussion and Conclusions

Out of the correlations explored, cement end-user indicators tend to demonstrate a stronger correlation with cement demand, with the exception of production in civil engineering works and roads development. This suggests that patterns in cement end-user indicators unfold patterns in cement demand behaviour. However, a single indicator cannot capture the whole picture behind the dynamics in cement demand development. For instance, the BPI serves as a good reflector of the development in cement demand but only considers demand from building constructions. A combination of indicators, each representing an end-user sector of cement, provides a more comprehensive picture of cement demand dynamics.

The trend analysis revealed that all cement end-user and supply indicators suffered from global emergency events such as the economic recession and the Covid-19 pandemic both on a country level and in the EU as whole. While the effect of such events varies across EU countries depending on regional characteristics, their impact on demand in the construction sector and consequently cement cannot be overlooked. However, socio-economic indicators exhibit a weaker correlation with cement demand due to external factors impacting the development of socio-economic indicators that do not directly influence or relate to cement.

In conclusion, a holistic approach that combines end-user sector indicators with broader socio-economic factors provides a more accurate and comprehensive picture of cement demand dynamics.

3 Cement Demand Forecasting Models

Predicting cement demand serves as the foundation for strategic planning within the cement industry (Kaur et al., 2023). It constitutes a crucial stage in crafting strategies for aligning production and trading with future market needs while supporting sustainability targets such as reducing CO_2 emissions. Accurate forecasts enable producers to align production capacities, optimize inventory management, make informed investment decisions, and adapt to market changes (Kaur et al., 2023). Additionally, it guides policymakers in meeting regulatory requirements and sustainability goals by directing investments in low-carbon technologies and alternative materials (Kaur et al., 2023).

Various methods are employed for cement demand forecasting in literature. Wei et al., (2019) use an econometric model to unveil the causal links between the cement demand dynamics and influencing factors, incorporating cross-correlation characteristics of system factors. However, during unforeseen events and external shocks impacting both socio-economic and cement demand dynamics, this approach might exhibit considerable irregular fluctuations, constraining their relevance in explorative scenarios (Xu et al., 2023). Tan et al. (2022) utilize analogical analysis, examining the dynamic features of cement demand in developed nations through analogical reasoning. This method is approached with probabilistic reasoning, aiming to induce and deduce objectives but faces limitations in setting specific values for peak times and saturation states (Xu et al., 2023).

Furthermore, Li et al., (2017) apply end-use forecasting, which identifies dynamic dependencies between the cement industry and various sectors. By summarizing the flow direction of end-use cement materials, this method forecasts and evaluates cement demand both in the terminal sector and the overall system. Constructing dynamic feedback relationships between cement demand dynamics and internal driving factors from the perspective of terminal downstream demand allows for more reasonable predictions of overall behavioural trends.

While the literature provides valuable insights into various cement demand forecasting methods, long-term energy models are widely used for their comprehensive approach to integrating energy demand projections with sector-specific analysis. This chapter examines the approaches of long-term energy models that include a specific module for the cement sector. To complement the analysis, an interview with an expert in demand forecasting was conducted. The aim was to identify key considerations for cement demand forecasting models, understand practical considerations and real-world applications, and address sub-question ii:

“How do current long-term energy models that include a specific module for the cement sector forecast demand in their approach?”

The chapter starts with explaining the methodology used to analyse long-term energy models in Section 3.1. The subsequent section, Section 3.2 provides detailed evaluations of the selected models, focusing on their approaches and limitations. Section 3.3 discusses the insights gained from the expert interview, while the chapter concludes with a summary of findings and recommendations for improving cement demand forecasting accuracy in Section 3.4.

3.1 Methodology

Five distinct models were examined which are the following: IMAGE (PBL Netherlands Environmental Assessment Agency, 2021), FORECAST (Fleiter et al., 2018), China Energy and Emission Paths to 2030 (Fridley et al., 2011), POLES (Després et al., 2018), and PRIMES (European Commission, 2023c). These models were identified through a comprehensive literature review. During the review process, other models were also encountered including TIMES (Loulou et al., 2016), Global Energy and Climate Model (IEA, 2023b) , and IRENA (IRENA, 2020). However, these models were excluded from the final analysis due to their limited focus on the cement sector. Most of these models incorporated cement demand and production within a broader non-metallic minerals category, providing insufficient granularity for the specific research objectives of this study.

The selection of models for this analysis was based on several criteria aimed at providing a comprehensive understanding of material demand and production projection methodologies in long-term energy models. Table 1Table 2 provides a summary of the criteria considered and the corresponding characteristics of each model that was included in the analysis. The first four criteria listed in Table 2 are intended to provide a brief summary of the methodology, level of detail, and scope of the models under review, while the other six criteria are more specific to the analysis of material demand and production projection methodologies, with a focus on the cement industry.

Table 2: Summary of the criteria considered for the selections of long-term energy models including POLES, PRIMES, IMAGE, FORECAST, and China Energy and Emission Paths 2030.

	POLES	**PRIMES**	**IMAGE**	**FORECAST**	**China Energy and Emission Paths**
Time horizon	2050	2050	2050	2050	2030
Regional coverage	Global	European countries	Global	European countries	China
Main drivers of material demand (Exogenous)	GDP, Population, Carbon Restriction, Resources	GDP/Economic Activity, Demography, Energy Sources World Market Prices, Technology Parameters, Policies/Directives, and Measures	GDP/Economic Activity, Population, Prices, Energy Sources, World Market, Technology Parameters,	GDP, Population, Sector Specific Drivers, Energy Sources, Technology, Parameters, Regional Market, Policies/Directives and Measures,	GDP, Population, Sector Specific Drivers, Regional Market
Macroeconomic framework data	Assumptions and studies	GEM-E3 projections	Non-linear inverse model	A hybrid model with top-down and bottom-up approaches	Assumptions and external studies (end-use model)
Specific module for the cement industry	No	Yes	Yes	Yes	Yes
Physical driver Sizes	Only for the steel industry	Yes but not clearly visible modelling	No	Yes	Yes
Trade of industrial products	Not mentioned	Top-down assumptions	Detailed modelling	Mentioned but not clearly visible modelling	Mentioned but not clearly visible modelling

Recycling strategies for industrial products	Mentioned but not clearly visible modelling	Top-down assumptions	Detailed modelling only for the steel industry	Detailed modelling with a focus on metals, paper, and glass industries	Top-down assumptions
Recycling strategies for cement	No	No	No	No	No
Material strategies of industrial products	Not mentioned	Mentioned but not clearly visible modelling	Detailed modelling	Detailed modelling	Mentioned but not clearly visible modelling

Among the selected models, IMAGE, FORECAST, and China Energy and Emission Paths to 2030 were chosen for a more in-depth analysis of their material demand and production projection methodologies. The decision was made based on the level of detail provided for the cement industry within each model and the availability of comprehensive sections discussing the methodologies and results within the available literature.

Moreover, an interview was conducted with Daniel Duffy, a seasoned demand forecasting expert. Duffy's background in operations management and extensive experience in supply chain management across various industries, particularly his current role as the Global Discipline Director of Materials Management at Hatch Engineering, highlights his expertise in matching supply with demand in complex supply chain scenarios. The interview aimed to spark discussion on general demand forecasting principles and their applicability to cement demand specifically. While Duffy's prior experience may not have included cement directly, his insights into broader demand dynamics and his informed opinion on best practices in forecasting methods proved valuable for this research.

3.2 In-depth Analysis of Long-term Energy Models

In this section various cement demand forecasting methodologies integrated into long-term energy models were examined. While five distinct models were identified (IMAGE, FORECAST, China Energy and Emission Paths, PRIMES, and POLES), a deeper analysis was conducted on only three. The decision was made based on the level of detail provided for the cement industry within each model and the availability of comprehensive sections discussing the methodologies and results within the provided literature. The following sub-sections provide a description of the methodological approach in IMAGE, FORECAST, and China Energy and Emission Paths models.

3.2.1 IMAGE Model

The modelling process for the cement industry in the IMAGE model (PBL Netherlands Environmental Assessment Agency, 2021) begins by projecting the physical demand for cement. The projections are determined in a non-linear inverse (NLI) model with an S-shape relation between GDP per capita and material consumption, following a similar approach to the one used by Neelis & Patel (2006) and Roorda & Neelis (2006). The per capita consumption is derived using Equation 1.

The equation reflects an S-shaped relationship where material consumption per capita initially increases rapidly with GDP per capita development but eventually levels off as income levels rise further. This derives from the arguments that the production composition of income evolves as a country develops, leading to a shift in demand towards more material-intensive sectors, followed by a transition towards less material-intensive products as development progresses (Neelis & Patel, 2006). Secondly, the material composition of products undergoes phases of replacement, characterized by initial expansion as new materials replace existing ones, followed by stabilization as demand saturates for the primary end-use of the material, and eventual decline as the material is increasingly substituted by alternatives (Neelis & Patel, 2006). Additionally, a third argument posits continuous improvements in material use efficiency, further influencing the declining consumption of material use observed in developed countries (Neelis & Patel, 2006).

$$PCC_t = \alpha * e^{(\frac{\beta}{GDP_{pc,t}})}$$

Equation 1

Where:

- $PCC_t =$ per capita consumption in year t (kg).
- $GDP_{pc}, t =$ GDP per capita in year t (€).
- α = shape parameter (saturation level of the per capita consumption at high-income levels)
- -β= shape parameter (per capita income level where material IU reaches its maximum)

The income elasticity of PCC describes how PCC responds to a variance in income. Equation 2 provides the derivation of the income elasticity, which is defined as the ratio of the percentage change in PCC to the percentage change in income. Parameter α represents the saturation level of PCC at high-income levels, as the income elasticity tends towards zero with increasing GDP per capita. Parameter -β indicates the income level at which the intensity use of material reaches its maximum. By definition, this per capita income level also marks the threshold at which the income elasticity of PCC equals 1. Below – β, the income elasticity of PCC is above 1, whereas above – β, it is below 1. To determine the overall consumption within a region, PCC is multiplied by the population size.

$$Income\ elasticiity: \frac{-\mathrm{\beta}}{\mathrm{GDP_{pc}}}$$

Equation 2

Subsequently, a cement production model simulates the fulfilment of cement demand. The production model operates by balancing cement demand through domestic production or trade with other regions. A vintage capital stock model depicts the evolution of cement-producing capital stock over time, incorporating proportional reductions for all plants in case of declining demand. The production model assumes existing facilities operate until a set lifespan and favours them over new constructions due to investment costs. Trade is modelled by allocating production capacity to global regions and determining new capacity installation based on technology market shares. The main drivers of trade are production costs, transportation costs, and trade barriers.

Moreover, the model uses Portland cement as the reference definition for cement and includes four production technologies that consist of different dry-feed rotary kilns, possibly combined with CCS. For each technology, assumptions on costs, specific energy consumption, energy efficiency improvements, and emissions of cement production plants are made. The model utilizes population and GDP projections as derived in the Shared Socioeconomic Pathway 2 (SSP2) scenario (Dellink et al., 2017).

Furthermore, Kermeli et al. (2019) included retrofitting of cement plants by integrating technical energy savings potential based on implementation rates of Best Available Technologies (BAT), and reducing the clinker-to-cement ratio by linking it with the availability of key SCMs to enhance the accuracy of the representation of the energy demand from the cement industry in the IMAGE model.

While the IMAGE model offers a comprehensive framework for projecting cement industry dynamics, its generalized assumptions and lack of detailed country-specific data can limit its accuracy and applicability to country-level modelling. It may benefit from incorporating more granular data and a bottom-up approach to better reflect the diverse economic and industrial landscapes of individual countries. Additionally, integrating physical demand calculations and detailed end-user demand information would further improve its ability to reflect diverse economic and industrial landscapes of individual countries.

3.2.2 FORECAST Model

The FORECAST model converts macroeconomic factors such as the GVA into physical tonnes of industrial production at the process level in order to calculate the energy demand of industrial sub-sectors (Fleiter et al., 2018). The model considers both the development of domestic demand and foreign trade for every industrial product, and based on its characteristics specific demand drivers are determined (Fleiter et al., 2018). The model utilizes projections of the development of GDP, population, energy prices, and the GVA based on the reference scenario of the ASTRA macroeconomic model from the European ASSIST project.(Krail & Schade, 2014). It is important to note that the ASSIST reference scenario indicates a particularly significant growth rate in both manufacturing and construction sectors (Herbst, 2017).

Further sectoral differentiations are made for the GVA projections which are specific to the demand drivers of each industrial product (Herbst, 2017). For the additional sectors included, the share of GVA in the base year was determined using empirical data from Eurostat, while the future development was determined using assumptions and an “experts” survey. For the cement industry, the construction sector is acknowledged as the main upstream supplier of cement in building constructions and civil engineering works (Fleiter et al., 2013). While the study includes the historical development of indicators in the cement industry of Germany which are considered for the future development of cement demand, a detailed description of the assumptions taken for the development of the construction sector is not provided.

In order to translate these economic or demographic indicators into physical drivers of energy demand, the model considers structural changes between (intra-sectoral structural change) and within (intra-industrial structural change) sectors. Intra-sectoral structural changes involve shifts in economic activity within sectors (i.e. transitions from energy-intensive industries to the production of consumer and capital goods) or the emergence of new economic sectors (i.e. waste and recycling management). Intra-industrial structural changes consider changes in demand (i.e.as a result of producing higher-value products), trends toward higher value creation (i.e. through product-related services), and/or changes in material strategies (i.e. as a result of increasing material efficiency/material substitution, and changes in recycling behaviours).

Furthermore, the model considers various process technologies during the production phase and includes a variety of saving options for each technology, as well as innovative processes of cement production (Fleiter et al., 2013). and the resulting GHG savings potentials for 2020 and 2035. Processes are described by a specific energy consumption factor and an activity size based on the model assumptions. Additionally, the model considers regional details of energy intensities and capacity utilization to make assumptions for the production projections in each process step.

The FORECAST model offers a robust framework for translating macroeconomic factors into physical tons of industrial production, including energy demand for industrial sub-sectors. It effectively incorporates projections of GDP, population, energy prices, and the GVA, with a particular emphasis on the significant growth rates in manufacturing and construction sectors as indicated by the ASSIST reference scenario. The model's consideration of both intra-sectoral and intra-industrial structural changes, along with its focus on various process technologies and energy-saving options, enhances its capability to project future energy demand and GHG savings potentials.

However, the model has limitations that impact its accuracy for cement demand forecasting. Specifically, it lacks a detailed analysis of the construction sector's future development and its effects on cement demand. Additionally, the model does not fully account for structural changes within the construction sector, which are crucial for a comprehensive understanding of cement demand dynamics. Incorporating detailed projections and assumptions about the construction sector's evolution would improve the model's ability to reflect the true drivers of cement demand.

3.2.3 China Energy and Emission Paths to 2030 Model

The methodology employed in the China Energy and Emission Paths to 2030 model (Fridley et al., 2011) for projecting cement demand captures the broad spectrum of activities during cement consumption in China. Cement production is determined through Equation 3, which accounts for new urban and rural commercial and residential construction, urban paved roads, expressways, highways, railways, and net exports of cement. The model integrates the development of demand for new floorspace and infrastructure by incorporating assumptions regarding the socio-economic and infrastructure development in China.

GDP is the key macroeconomic factor in the model, directly impacting industrial production, trade, and household income, which in turn affects consumption patterns. However, the model description lacks information on how GDP is specifically linked to changes in floorspace. Moreover, the growth of China's GDP is also directly linked to its labour market and structure, whereby the expansion of service sector-oriented employees drives commercial floorspace demand. Population growth and urbanization rates represent another significant factor driving cement demand in the model, reflecting the understanding that as more people migrate to urban areas, there is a corresponding increase in the demand for housing, commercial spaces, and infrastructure, all of which heavily rely on cement.

Figure 9**Error! Reference source not found.** visualizes China's commercial and residential building floorspace outlook as integrated into the model. Additionally, the model acknowledges a lifespan for buildings, assuming a short 30-year lifespan which drives an increase in cement demand after 2020 in the model. The growth of urban paved areas and highways is simulated based on the Japanese model of infrastructure development, while insights from the Chinese railway development plan are incorporated into the model to ensure alignment with the expected expansion of infrastructure networks. To calculate the final annual cement demand, material intensities of cement in different end-uses are multiplied by the physical demand of each activity (in m^2), derived from the assumptions integrated into the model. However, there is no indication provided regarding whether the material intensities change over time, implying an assumption that material intensities remain constant over time (Herbst, 2017).

$$P_c = [(CFS_u + CFS_r) * CI1 + (RFS_u * CI2) + (RFS_r * CI3)] + (PA * CI4) + (H * CI5) + (R * CI6) + Ex$$

Equation 3

Where:

- P_c = Annual cement production (kg)
- CFS_u =Urban commercial floorspace - 3 year rolling average (m^2)
- CFS_r =Rural commercial floorspace -3 year rolling average (m^2)
- RFS_u =Urban residential floorspace - 3 year rolling average (m^2)
- RFS_r =Rural residential floorspace- 3 year rolling average (m^2)
- $CI1$ =Commercial building cement material intensity (kg/m^2)
- $CI2$ =Urban residential building cement material intensity (kg/m^2)
- $CI3$ =Rural residential building cement material intensity (kg/m^2)
- PA =Urban paved area (km)
- $CI4$ =Paved area cement material intensity (kg/km)
- H =Highways, specifically expressways, and Class 1 and 2 highways - 3 year rolling average (km)
- $CI5$ =Highway cement material intensity (kg/km)
- R =Railroad track length- 3 year rolling average (km)
- $CI6$ =Railroad track cement material intensity (kg/km)
- Ex = Net exports of cement (kg)

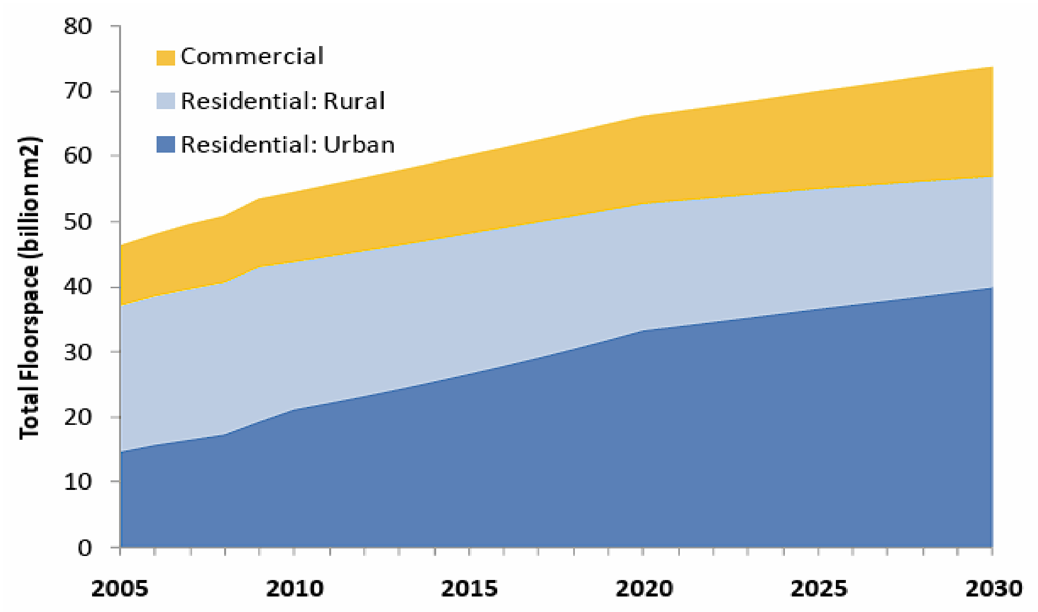

Figure 9: China's commercial and residential building floorspace outlook as integrated into the China Energy and Emission Paths 2030 model (Fridley et al., 2011).

In conclusion, the China Energy and Emission Paths to 2030 model effectively captures the broad spectrum of activities influencing cement demand in China, including new building construction, infrastructure development, and net exports. By integrating socio-economic factors such as GDP, population growth, and urbanization, the model provides a detailed projection of cement demand based on various end-users.

However, the model could be enhanced by incorporating further sectoral differentiation within the construction sector and accounting for structural changes over time. Specifically, further refinement in the assumptions about material intensities and adjustments for evolving construction practices could improve the accuracy of future cement demand projections. Incorporating these aspects would provide a more nuanced understanding of how changing dynamics within the construction sector impact cement consumption.

3.3 Expert Interview

Duffy emphasized the importance of considering both short-term and long-term factors influencing cement demand. He highlighted that short-term factors might include immediate market trends and economic fluctuations, while long-term factors encompass demographic changes, technological advancements, and policy impacts. His expertise also underscored the need for simplicity in a forecasting model, noting that overly complex models can lead to diminished clarity and potential inaccuracies. Striking the right balance between model complexity and usability is essential for effective demand forecasting. Additionally, the interview served as a validation step for the research findings, ensuring that the approaches and assumptions made in the analysis align with industry standards. Duffy's feedback helped affirm the robustness of the methodologies employed and provided practical insights into integrating market intelligence and ensuring data quality in forecasting.

Overall, the interview with Duffy enriched the research by providing expert validation, practical insights, and strategic perspectives, thereby enhancing the overall quality and reliability of the study's findings on cement demand forecasting in long-term energy models.

3.4 Discussion and Conclusions

All models include macroeconomic and demographic factors as drivers of cement demand. However, the process of translating these factors into physical demand differs in each model. A hybrid approach that considers both top-down and bottom-up details of the cement industry represents the most comprehensive approach. Additionally, incorporating alternative macroeconomic scenarios to account for potential uncertainties and provide a broader range of possible futures for cement demand and production can enhance the accuracy of projections. Key considerations for future modelling of cement demand in long-term energy models are listed below:

- **Physical demand:** Directly modelling the physical demand for cement can provide a more comprehensive picture (Kermeli et al., 2019; Fleiter et al., 2018; Fridley et al., 2011).

- **End-user demand:** Incorporating bottom-up details on direct demand from end-users can enhance the model's accuracy (Fleiter et al., 2018; Fridley et al., 2011).

- **Regional details**: Incorporating regional details of the historical development of the end-users of cement can provide a more granular picture of cement demand. This includes trends in construction such as material intensity, average building floor space, floor space per capita, as well as socio-economic indicators and the overall policy landscape.

- **Construction sector structural changes:** Incorporating sectoral differentiation (Fridley et al., 2011) and circular economy activities (Fleiter et al., 2018; PBL Netherlands Environmental Assessment Agency, 2021) of the construction sector such as renovation and adaptive reuse of buildings or utilizing RCA in infrastructure projects can improve the model's reflection of cement demand shifts in the end users of the construction sector.

All models explored technological advancements in the cement industry, accounting for differences in energy demand from the production process. While this does not necessarily impact the development of cement demand in the models since the focus is on energy demand, it allows for a more nuanced understanding of how technological improvements can influence overall the energy consumption derived from cement production. Key considerations for future modelling of cement production in long-term energy models are listed below:

- **Cement industry structural changes:** Integrating material efficiency strategies like reducing the clinker-to-cement ratio from the use of available SCMs, and including technological development such as BAT practices in cement plants can enhance the model accuracy (Kermeli et al., 2019; PBL Netherlands Environmental Assessment Agency, 2021; Fleiter et al., 2018;).

- **Processes in production:** Differentiating the activity size of the process in production can provide a more nuanced understanding of energy consumption patterns within the cement industry (Fleiter et al., 2013).

- **Trading:** Explicitly modelling trade flows of cement can improve the accuracy of regional cement demand projections. On a global scale, this requires the incorporation of production costs, transportation costs, and trade barriers into the model framework (PBL Netherlands Environmental Assessment Agency, 2021). On the regional scale**,** considerations should include regional details of the cement industry, such as cement plant capacity size, plant retirement age, and plans for new capacity developments.

- **Recycling:** Integrating the potential of increasing cement recycling rates into the models can enhance their ability to capture future demand shifts. While none of the models explicitly consider cement recycling, acknowledging growing trends of cement recycling practices and the potential influence on demand is crucial for long-term projections.

In conclusion, this analysis highlights the need for a comprehensive modelling approach for the cement industry that considers various aspects. By integrating physical demand calculations, construction sector dynamics, and technological advancements in both end-use sectors and the cement industry, future models can provide more accurate and informative projections.

4 Cement Demand Forecasting Framework

The cement industry operates within a complex socio-economic system, making it interdependent and sensitive to various influencing factors. Economic conditions, societal changes, and technological advancements all play a crucial role in in shaping cement demand (Xu et al., 2023). For instance, construction activity, which is the main end-user sector of cement, is closely tied to the health of the economy, making it highly susceptible to fluctuations in economic activity (Sverdrup & Olafsdottir, 2023). The expansion of urban areas spurs increased cement consumption due to intensified infrastructure development and a rise in both residential and non-residential construction projects (Xu et al., 2023). Technological advancements in the cement industry and its end-user sectors can impact directly or indirectly cement consumption by introducing new cement products or production processes, as well as new construction technologies, influencing demand patterns (Naqi & Jang, 2019; Cruz et al., 2023; Lu et al., 2024). Additionally, fluctuations in energy costs can directly affect production costs, influencing the pricing and demand for cement (Ighalo & Adeniyi, 2020)., while the availability and cost of raw materials, such as limestone, clay, and SCMs, play a significant role in production and demand dynamics (Ige et al., 2022).

Existing cement demand forecasting models fall short in capturing the intricate relationship between cement demand and its underlying drivers. Robust modelling of cement demand necessitates a holistic approach that incorporates detailed sector-specific details, physical demand drivers, and the dynamic influences of socio-economic and technological developments, especially within the EU context. Understanding these factors is crucial for accurate demand forecasting and strategic planning within the cement industry, ensuring that producers can adapt to evolving market conditions, while policymakers can align policies and regulations to facilitate the transition to a low-carbon economy and support sustainable cement production and consumption.

This chapter details the development of a framework specifically tailored for forecasting cement demand at the country level within the EU27 region, while Chapter 5 focuses on modelling and validating the accuracy of this framework in a case study. The framework focuses on modelling the regional cement demand of European countries individually and does not incorporate the dynamics of cement production and trading. In this way, complexities associated with inter-regional cement production and trade dynamics are not included. The aim of the developed framework was to capture a broad picture of the factors influencing cement demand across the EU27 Member States, how they are interconnected, and address research sub-question iii:

"Which factors should be included when forecasting and modelling cement demand in the EU27 region and how are they interconnected?"

In the upcoming sections, Section 4.1 details the methodology employed in this chapter. Section 4.2 describes the conceptual framework developed, outlining the key variables and their interconnections.

4.1 Methodology

The framework was developed by synthesizing insights from the previous chapters, which included trend and correlation analyses, key considerations derived from long-term energy model approaches, and an expert interview. The first step involved critically evaluating the relevance and predictive power of each indicator that emerged from analysing consistent drivers and fluctuations in cement demand over the studied period. This assessment focused on understanding how consistent drivers and fluctuations in cement demand influenced cement demand dynamics. The next step included evaluating the methodologies and applicability of long-term energy models for cement demand forecasting. Insights from Duffy's opinion were incorporated to ensure that the framework adhered to key principles and best practices in demand forecasting.

Based on these evaluations, a comprehensive understanding of the factors influencing cement demand, and their interconnectivity emerged. The developed framework employs a bottom-up approach to estimate cement demand based on end-user activities, incorporating physical measures of the construction sector. To enhance the model’s predictive power, top-down factors such as socio-economic trends were integrated into the framework. The integrated approach ensures that both end-user activities and broader socio-economic factors are accounted for, providing a robust foundation for forecasting future cement demand in the EU27 region.

4.2 Key Drivers and Influences in Cement Demand Forecasting

Figure 10 illustrates the developed framework for forecasting cement demand. The following sub-sections delve into the details of the framework.

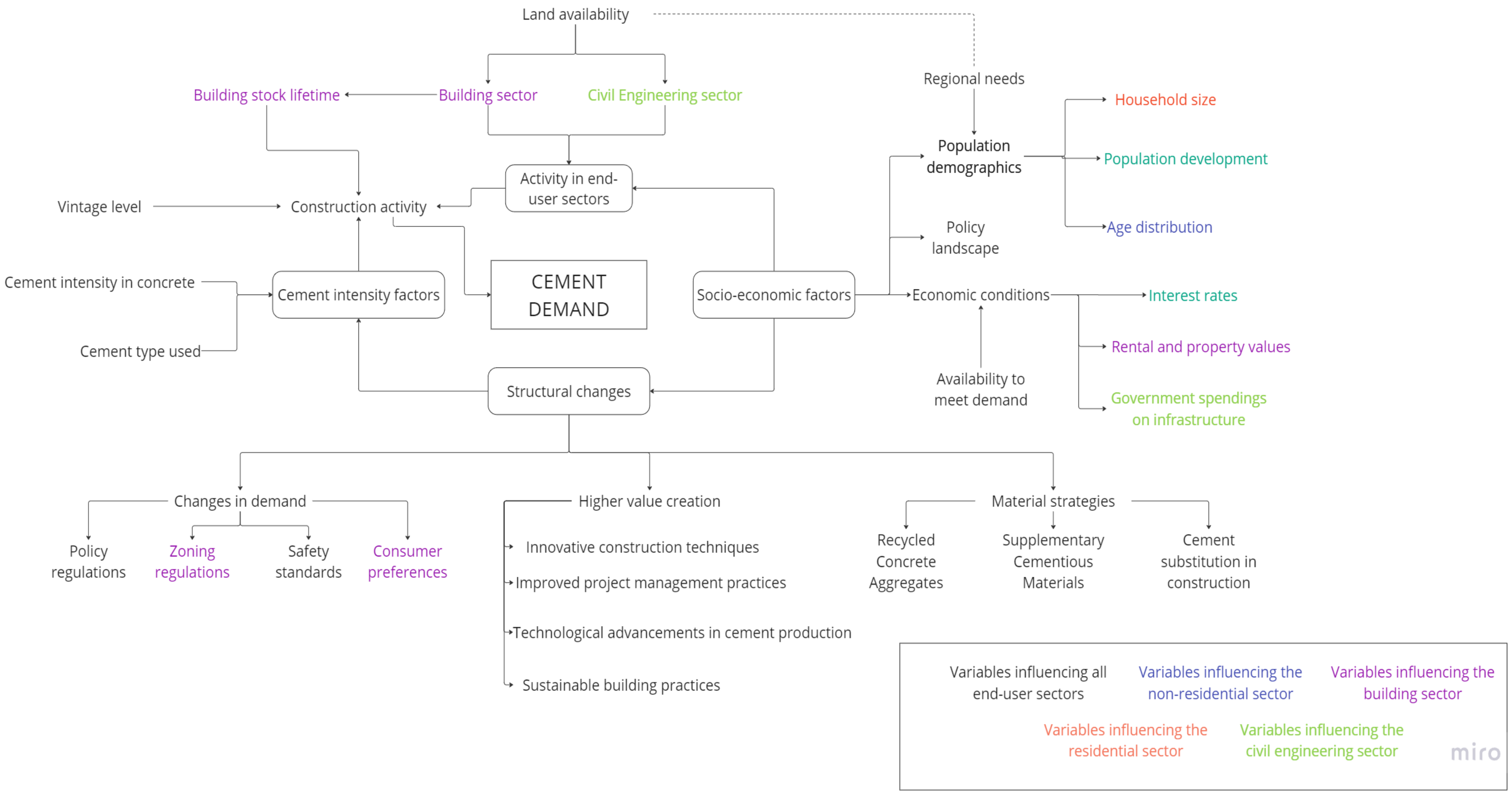

Figure 10: Conceptual framework for forecasting cement demand, as developed in this study.

4.2.1 Socio-Economic Factors Influencing Cement End-User Sectors

4.2.1.1 Residential sector

Population growth offers valuable insights into the expected demand for new residential buildings. A rising population necessitates expanding the housing supply to accommodate more residents. However, solutions for accommodating a growing population depend on regional characteristics and policy decisions. Land availability shapes the feasibility and scope of development initiatives (Ede, 2014). Limited availability of land might require building high-rise structures or densifying existing urban areas. The lifespan of the current building stock is equally crucial. A well-maintained housing stock with a longer lifespan can potentially accommodate more occupants in the short term through adjustments, reducing the immediate need for new construction and associated cement demand (Beer et al., 2014). Conversely, aging and poorly maintained infrastructure could exacerbate the need for new constructions and retrofitting activities, leading to increased cement consumption.

Economic conditions, while not directly impacting the physical demand for new residential buildings, determine the availability of resources to meet that demand and the level of comfort that can be afforded. This in turn, directly affects cement demand. Strong economies can stimulate construction activity across various sectors including the residential, commercial, and civil engineering sectors, leading to increased cement demand (Sverdrup & Olafsdottir, 2023). Conversely, economic downturns can lead to a decrease in investment and project delays, impacting cement consumption. Moreover, interest rates also play a significant role. Lower interest rates can make borrowing for construction projects more affordable, potentially boosting demand for cement in the short term (Sverdrup & Olafsdottir, 2023). Contrarily, rising interest rates might have a dampening effect on construction activity and cement demand (Sverdrup & Olafsdottir, 2023).

Household demographics, particularly household size and composition are also crucial factors driving the physical demand for cement in construction activities in the residential sector (Abalos & Yeung, 2023). An increase in single-person households can contribute to a preference for dwellings with a smaller average floor area. This can potentially reduce the overall cement consumption per household construction. However, a trend towards smaller household sizes with fewer occupants might result in a proportional need for new buildings, leading to increased cement demand. On the other hand, the existing housing stock might be able to accommodate a higher number of occupants in the short term as adjustments are made. While this could lead to increased demand for renovation and retrofitting activities, it may delay the need for new construction (Paolo, 2007).

4.2.1.2 Non-residential sector

The development of commercial buildings in a region is also driven by an interplay between demographic factors and economic conditions. As cities expand, the demand for commercial spaces rises (Lehmann, 2019). Urban areas attract businesses, offices, and retail establishments, prompting developers to build office buildings, shopping centres, and mixed-use developments. High population densities are frequently associated with an increase in commercial development, particularly in central business districts, which accommodate restaurants, entertainment venues, and offices.

The age distribution is another influential factor. An aging population may drive demand for healthcare facilities such as hospitals, clinics, and assisted living centres (Osareme et al., 2024).

Conversely, a younger demographic may favour the development of entertainment venues like cinemas, concert halls, and sporting facilities. As different age groups drive the need for specific types of infrastructure, cement consumption patterns in the non-residential sector adjust accordingly. Thus, the age composition of a population influences the types of non-residential buildings constructed, and since different building types require varying amounts of cement, it directly affects the overall cement demand.

Furthermore, the impact of economic cycles on cement demand in the non-residential building sector is a complex interplay between several factors. A thriving job market attracts businesses, which in turn, require non-residential building spaces. Conversely, economic downturns can lead to business closure, freeing up existing building spaces. However, different non-residential sectors have varying space needs, growth trajectories, and target audiences. Consequently, each sector reacts uniquely to economic conditions. For instance, the technology and healthcare sectors may continue to grow even during economic downturns, while sectors like retail and hospitality may see significant contractions (Bénétrix & Lane, 2010). Additionally, shifts in work patterns, such as the rise of remote work, can alter the demand for office spaces (Oladiran et al., 2023).

These economic shifts also impact the dynamics of the non-residential real estate market, potentially affecting rental rates and property values (Alaloul et al., 2022). In such times, the focus may shift to renovating and repurposing existing structures to attract new tenants rather than constructing new buildings, which can still sustain some level of demand for cement, albeit differently. Understanding these nuances is crucial for anticipating the overall cement demand in the non-residential building sector.

4.2.1.3 Civil engineering sector

While construction activities in the civil engineering sector are also driven by a similar interplay between socio-economic factors, government spending plays a vital role in shaping the development of these projects. Local authorities typically subsidize civil engineering projects through mechanisms like grants, tax incentives, and public-private partnerships (Ortiz-Ospina & Roser, 2023). Infrastructure needs are typically driven by urbanization and population growth, as rapid urban expansion and increasing population creates demand for new and upgraded infrastructure. Economic cycles, in turn, determine the level of government spending on these projects. Increased revenue enables higher public investment in infrastructure projects, boosting cement demand. Conversely, economic downturns lead to budget cuts, reducing spending and subsequently cement consumption in infrastructure projects.

Therefore, local government plans and budgets provide valuable insights into the anticipated cement demand in the civil engineering sector. Analysing the specific types of infrastructure projects such as roads, bridges, and public facilities planned for construction or maintenance in a region can inform detailed short-term forecasts of cement demand. For long-term forecasting, it is essential to consider broader trends in urbanization, population growth, economic cycles, as well as potential shifts in government priorities and technological advancements in infrastructure. These factors collectively influence the future demand for cement, helping to build a comprehensive understanding of the sector's evolving needs.

4.2.1.4 Regional policy landscape

The regional policy landscape plays a crucial role in shaping construction activities and cement demand across different regions. This landscape encompasses a range of regulations, incentives, and strategic initiatives that impact economic development, infrastructure projects, and the built environment. Understanding the policy context is essential for accurately forecasting regional cement demand, as policies directly influence both supply and demand dynamics in the construction sector and the cement industry.

Government regulations and incentives significantly affect cement demand by shaping construction practices and cement production processes. Policies that provide tax incentives for sustainable building practices or green building materials may initially drive a shift towards alternative materials that have a lower environmental impact than traditional cement (Cruz et al., 2023). For example, incentives that encourage the use of SCMs can reduce the clinker-to-cement ratio in cement production, thereby decreasing the volume of cement required in concrete mixtures.

The implementation of carbon pricing and the removal of free allocations have the capacity to increase cement prices, potentially reducing demand as construction projects seek more cost-effective alternatives (Heincke et al., 2023). These policies can incentivize the development and use of low-carbon cement and alternative materials, further influencing the dynamics of cement supply and demand in a region. By encouraging the adoption of sustainable materials, these policies can shift supply towards more environmentally friendly options and decrease the reliance on traditional cement. This shift can lead to increased innovation and investment in alternative materials and production processes, ultimately altering the balance of supply and demand in the cement market.

Government initiatives aimed at urban development, housing, and transportation can significantly boost cement consumption (European Commission, 2023a). Conversely, delays or reductions in public infrastructure spending can dampen demand for cement. Moreover, changes in zoning regulations and evolving safety standards can significantly impact construction practices and consequently cement demand (Vagtholm et al., 2023). For instance, zoning regulations that promote higher-density developments, such as high-rise apartment complexes or mixed-used buildings, can increase the demand for cement due to the larger structural requirements of these projects. Additionally, enhanced building codes for earthquake resistance, fire safety improvements, and other structural integrity measures necessitate adjustments in construction practices, which can increase the demand for cement. These standards often require more robust construction techniques and materials, thereby influencing the amount and type of cement used in various projects.

4.2.2 Activity in End-User Sectors

The framework considers buildings and civil engineering works as the primary and only end-user sectors of cement demand. Central to this approach is breaking down these end-user sectors further into project types commonly found within the region under study, examining different construction activities taking place, and assessing the specific vintage level of each construction activity. By accounting for these factors, the framework captures variations in cement intensity and levels of activity for each case. This detailed analysis enables a more precise estimation of cement demand within the framework. The way these factors affect cement demand is discussed in section 4.2.3. The following sub-sections describe the indicators and data sources that can be used to estimate cement demand from cement end-user sectors, detailing how the chosen metrics and data are relevant and useful for understanding demand in the building and civil engineering sectors.

4.2.2.1 Indicators for the building sector

For the buildings sector, while the BPI provided by the Eurostat database offers a combination of physical and end-user demand insights, it falls short in its ability to disaggregate building types. However, some national statistical databases such as the CBS National Statistics of the Netherlands, provide a more detailed breakdown of building permits, categorizing residential building permits into one-dwelling, two or more dwellings, and residential communities, and non-residential building permits into offices, and other non-residential buildings. A detailed description of the definition of these categories is provided in Section 2.2, on page 12. The availability of such data enables the disaggregation of building types in the framework. However, further granularity in the disaggregation of building types would enhance the accuracy of the framework.

Furthermore, obtaining data on different construction activities within a region poses challenges, since the BPI does not distribute between new construction permits and maintenance/retrofit permits. Although, national statistical databases such as the CBS National Statistics, provide data for the number of new construction buildings in their national housing stock. However, this measurement does not include information on the total floor area (m^2) of new constructions, making it difficult to estimate the actual level of activity in new construction projects.

To address this challenge, an average floor area for each building type could serve as the basis for estimating the floor surface area of new building constructions within historical BPI data. This process involves several steps, starting by calculating the proportion of each residential or non-residential building type within the total number of residential or non-residential building permits issued in a given year. This yields the percentage representation of each building type. Subsequently, multiplying these percentages by the total number of new building constructions as shown in Equation 4 provides an estimation of the number of new constructions for each building type.

$$New\ constructions_{building\ type}\ (num.) = Share\ of\ building\ type\ in\ BPI\ (\%) * Total\ new\ constructions\ (num.)$$

Equation 4

Assuming an average floor area for each building type based on historical data and multiplying it by the number of new constructions for each building type, derives the total floor area of new constructions per building type within the region as shown in Equation 5. The difference between this estimation and the permits issued could potentially reveal the number of square meters permitted for construction activities other than new constructions.

$$Total\ floor\ area\ of\ new\ constructions\ (m^2) = New\ constructions\ (num.) * Average\ floor\ area (m^2)$$

Equation 5

4.2.2.2 Indicators for the civil engineering sector

For the civil engineering sector, Eurostat's online database provides a snapshot of civil engineering project types, including data on squared kilometres of roads, railways and airport runways in a region. However, these measurements alone do not capture the nuances of cement demand specific to each project type, except from roads, where a more detailed dataset is available including different types of road constructions. For example, the indicator for railway construction measures the area of the railway. While railway tracks utilize concrete for the sleeper that supports the rails, railway construction projects primarily utilize cement for bridges, and stations during construction.

Additionally, airplane runways are specialized infrastructure projects where maintenance activities may be more frequent due to wear and tear caused by aircraft landings and take-offs. Since the specific construction activity taking place cannot be distinguished through the available data, these indicators may prove to be irrelevant when estimating the cement consumed in such projects. Moreover, the dataset excludes the dataset from other more significant consumers of cement, especially for structures such as bridges, and tunnels.

Therefore, the current data from Eurostat do not sufficiently capture specific cement demands over various civil engineering projects, nor do they distinguish between different types of infrastructure works. This limitation makes it challenging to accurately estimate cement consumption based on the available physical measurements alone.

An alternative way to model cement demand from civil engineering works is to look at the GVA in constructions attributed to the sector alone. While this is a monetary indicator that includes factors that are not directly related to cement demand such as labour costs and equipment rentals, the GVA in construction attributed to civil engineering works can still provide valuable insights when compared with the GVA in construction attributed to buildings.

This comparison can reveal insights into the relative scale of civil engineering activity compared to building construction. In this way, a relationship between the monetary value of civil engineering works and the associated cement consumption can be established. This relationship can be then used to estimate cement demand for civil engineering projects based on their anticipated GVA. While this approach does not model the physical demand for cement in civil engineering projects, it offers a complementary perspective to the bottom-up approach.

Eurostat's GVA in construction dataset does not differentiate between buildings, civil engineering works, and other specialized activities. However, national statistical databases provide a more comprehensive breakdown of the indicator, allowing us to estimate the relative contribution of civil engineering works in the total GVA in construction within a region.

4.2.3 Cement Intensity Factors

Acquiring data on average cement intensity factors for each building and civil engineering project type specific to the region under examination is essential for the successful application of the framework. Cement intensity in each construction activity and project type depends on specific characteristics of the project (Lafhaj et al., 2024). Each project type is likely to have a distinct cement intensity factor due to differences in size, complexity, and structural design. These factors determine the final cement consumption for a project.

In the building sector, different types of residential building types, such as detached houses, terraced houses, or apartment complexes, have distinct cement intensity factors. For example, a high-rise residential apartment building will generally require more cement per unit area compared to a low-rise apartment building due to its greater structural demands. Similarly, the construction of a commercial building with complex design features such as intricate facade elements will have different cement intensity requirements compared to a design focused on large open spaces or extensive use of glass.

In the civil engineering sector, the cement requirements can also vary widely depending on the type of project (Okae-Adow et al., 2015). Road constructions, for instance, might involve varying quantities of cement depending on the type of road and its structural requirements. Additionally, bridge constructions can exhibit significant differences in cement intensity based on factors such as span and design complexity, as well as the environmental conditions the infrastructure will endure.

Moreover, new construction projects will naturally require larger quantity of cement compared to retrofitting and maintenance activities. Meanwhile, demolition activities can increase the availability of RCA and potentially reduce demand for virgin cement. The vintage level of each construction activity also impacts cement demand. For instance, residential buildings may be classified as new construction, advanced new construction, light retrofit, or advanced retrofit, each with varying cement needs.

Different concrete formulations also require varying amounts of cement. The type of concrete, whether reinforced, prefabricated, or otherwise, and its desired properties such as strength, durability, and workability, influence cement demand (Dehghan et al., 2023). For instance, high-strength concrete used in structural applications will necessitate more cement than standard concrete mixes. Additionally, specialized concrete types designed for unique environmental conditions, like high-performance concrete for marine environments or fibre-reinforced concrete for seismic zones will have distinct cement requirements (Dehghan et al., 2023). The use of additives and admixtures in cement production, such as fly ash or slag can alter the cement content required to achieve specific characteristics, making the choice of cement type crucial (Dehghan et al., 2023). Furthermore, the specific mix design, including water-cement ratio and aggregate selection, also play a significant role in determining the total cement needed for a project (Dehghan et al., 2023).

Factors such as design complexity, site conditions, construction practices, expertise, and client-driven design changes can lead to variations in cement demand, potentially causing underestimations or overestimations when relying solely on average intensity factors (Zamora-Castro et al., 2021). Nevertheless, accounting for variations down to the level of every single construction project within a region becomes impractical due to the sheer volume of data required. This highlights the need for a balanced approach that leverages the efficiency of end-user indicators and intensity factors while acknowledging their limitations.

In response to these challenges, average cement intensity factors can be assumed. However, the accuracy of average cement intensity factors depends on data quality and availability. Average cement intensity factors might differ between different European countries due to differences in building regulations and infrastructural development needs (Meijer & Visscher, 2008). Therefore, it is important to consider geographic specificity when applying average cement intensity factors to account for regional variations and enhance the accuracy of cement demand estimates.

4.2.4 Structural Changes

Changes in demand, trends to higher value creation, and changes in material strategies are amongst the key areas where structural changes can occur (Herbst, 2017). Structural changes affecting cement demand in a region involve shifts in the construction sector, where most of the cement is consumed, and shifts in the supply chain of the cement industry. These structural changes can occur due to advancements in technology and resource management, and changes in the socio-economic structure including shifts in zoning regulations, the policy landscape of the region, evolving consumer preferences, heightened environmental and safety standards, and economic fluctuations triggered by unexpected global events (Saviotti et al., 2020).

4.2.4.1 Structural changes in the construction sector

Shifts in the way buildings are designed, constructed, and maintained can have a lasting impact on the construction sector and its recourse consumption. The long-term importance of renovating existing structures within Europe is emphasized through the Energy Performance of Buildings Directive of the European Commission (European Commission, 2021). This directive underscores the need to improve the energy efficiency of buildings, thereby driving demand for renovation and retrofitting projects. While this increased focus on renovation and retrofitting projects can lead to higher demand for cement due to the need for materials in these projects, it can also have the opposite effect over time (IEA, 2023a). By extending the lifespan of existing buildings through renovation or retrofitting, the need for new construction projects may diminish. Consequently, this can result in reduced cement demand, as new construction typically requires significantly more cement compared to renovation and retrofitting activities.

Moreover, adaptive reuse, a strategy where existing buildings are repurposed for new users rather than demolished and replaced, has gained increasing attention in Europe in recent years due to sustainability concerns (Takva et al., 2023). This approach reduces the need for new construction, thereby lowering the overall cement demand (Takva et al., 2023). By avoiding demolition and new construction, adaptive reuse minimizes the consumption of cement and supports a more sustainable approach to urban development (Takva et al., 2023).

Furthermore, material strategies in the construction industry are evolving, with a growing emphasis on sustainability and efficiency. This shift is often driven by policies aimed at reducing environmental impact and promoting the use of sustainable materials (Almusaed et al., 2024). The industry is increasingly focusing on recycling concrete waste to enhance sustainability and reduce reliance on virgin raw materials (Kristanto et al., 2024). This involves reclaiming and reprocessing concrete waste usually sourced from demolition sites or construction projects (McNeil & Kang, 2013). The process entails crushing and grinding discarded concrete, transforming it into a granular material known as Recycled Concrete Aggregate (RCA), which can be incorporated back into the production process (McNeil & Kang, 2013).

According to the European Cement Association (2023a), it is necessary that the current separation and treatment methods improve in order to produce raw material of sufficient quality and handle greater quantities. This is relevant not only to the separation of concrete from hardened cement but also to the separation of concrete from other construction materials (European Cement Association, 2023a).The increased use of RCA in building structures can be supported by government incentives that promote the development of efficient methods for sorting and processing recycled materials (Z. Li et al., 2024). Similarly, material substitution strategies, such as replacing cement with wood or bio-based materials, are driven by growing awareness of their environmental benefits and supportive policies. The adoption of cross-laminated timber for high-rise buildings and the use of waste-based materials are examples of how material strategies are changing in response to sustainability goals (Howard et al., 2021).

Technological advancements achieving innovative construction techniques and improved project management practices contribute to higher value creation (Ke et al., 2023). Modular construction techniques, for instance, involve the use of prefabricated components, which can reduce material waste, on-site labour, and construction time (Wilson, 2019). In addition, the development of high-strength concrete can reduce the overall volume of cement needed for certain projects while still meeting the structural requirements (Cruz et al., 2023). These trends are driven by the need for greater efficiency and cost-effectiveness in construction projects.

Investment in automation and robotics for specific construction tasks, such as brick-laying robots, automated framing systems, and 3D printing, further enhances efficiency and precision in the construction process (Chea et al., 2020). Moreover, advancements in project management tools, such as Building Information Modelling (BIM) enable real-time coordination among architects, engineers, and contractors, leading to fewer errors and reduced reworks, thus reducing cement wastage and optimizing material use (Babalola et al., 2021).

4.2.4.2 Structural changes in the cement industry

The cement industry itself is undergoing significant structural changes, driven by various factors including the decarbonization of the industry, the ECT carbon pricing, the removal of free allocations, rising production costs, the availability of financial and raw material resources, the competitiveness of the industry, and the ability of the cement producers to cope with these issues (Harder, 2024). While these changes are crucial for ensuring the long-term sustainability and economic viability of the industry, they may not directly influence the demand for cement.

However, these structural changes can indirectly affect demand by altering the cost structures and competitive dynamics within the market. For example, innovations related to clinker substitution such as SCMs and optimized raw material mixes, are primarily aimed at reducing the overall carbon footprint of cement production (Leese, 2021). Similarly, technological advancements like advanced grinding technologies, utilization of waste heat in the production cycle, and adoption of alternative fuels strive to optimize production processes to minimize energy consumption and clinker content (Leese, 2021). Although these innovations do not directly affect cement demand, they can significantly impact production costs and market prices. Lower production costs resulting from these innovations can make cement more competitively priced compared to alternative building materials, thereby influencing the overall cement demand dynamics (Leese, 2021).

For example, despite the advanced sustainability and performance benefits of CEM IV and CEM V, CEM II and CEM III are experiencing greater popularity (Xavier & Oliveira, 2021). This increased preference can be attributed to several factors. CEM II and CEM III are often more cost-effective due to their relatively lower production costs and established production processes (Tait & Cheung, 2016). Additionally, these types of cement have broader acceptance and availability in the market compared to CEM IV and CEM V, which may require more specialized production techniques and raw materials (Ajumobi, 2020). While CEM IV and CEM V offer significant environmental benefits and performance enhancements, their higher costs and specialized production requirements can limit their use. Consequently, as the industry adapts to environmental pressures, CEM II and CEM III are increasingly favoured in Europe, leading to a decline in the market share of CEM I, which was previously the most widely used type (Xavier & Oliveira, 2021).

Moreover, the availability of financial and raw material resources determines the industry's capacity to produce and supply cement efficiently (Heincke et al., 2022). For example, a shortage in limestone supply could lead to a reduction in clinker production, potentially affecting the supply of cement in a region, as seen in the Dutch cement industry. Additionally, the decline in coal use, which is a key source of fly ash, reduces the availability of high-quality SCMs (Duchesne, 2021). This impacts the production of low-carbon cement, highlighting the need for ASCMs to ensure the long-term sustainability of the cement industry (Duchesne, 2021). Constraints in these areas could limit production capabilities and affect market supply, indirectly impacting demand dynamics by potentially increasing cement prices and influencing the adoption of alternative materials or technologies (Heincke et al., 2022). The industry's overall competitiveness, shaped by these structural changes, determines its ability to capture market share and respond to global and regional demand fluctuations effectively.

5 Framework Validation: Netherlands Case Study

This chapter focuses on the validation and testing of the cement demand forecasting framework developed to estimate cement demand within EU27 countries, using the Netherlands as a case study. To operationalize the framework, an Excel-based model was employed, which was initially validated by comparing its output with historical cement demand data for the Netherlands, as outlined in Chapter 2 of this research. The objective of this chapter is to assess the level of detail of the framework when applied to a specific country and address sub-question iv:

"How detailed can the application of the developed framework for forecasting cement demand be in a case study for an EU27 country when looking at easily available data sources?"

The chapter begins with the methodology in Section 5.1. Section 5.2 covers the current state of the construction and cement industries of the Netherlands, including relevant socio-economic factors. Section 5.3 details the modelling steps and validation for forecasting cement demand. Section 5.4 discusses the assumptions made in the developed scenarios, projected results, and sensitivity analysis. Finally, Section 5.5 reviews and concludes the chapter's findings.

5.1 Methodology

The Netherlands was chosen for this case study primarily due to its robust and accessible data on key variables relevant to cement demand forecasting. While the conceptual framework for forecasting cement demand includes a variety of indicators influencing cement demand in a region, only the indicators marked with an "X" in Table 5 were included in the model. The civil engineering sector was excluded from the model. This is because of limited data for construction GVA forecasts, as well as the time constraints of this research, which did not allow for the development of a comprehensive forecasting model for the civil engineering sector. Furthermore, the non-residential building sector was excluded from projections due to the limitation of easily available data sources for average floor surface areas of different non-residential buildings which constrained the projection of newly constructed floor surface areas in the sector. However, the historical cement demand from the non-residential sector was modelled to complement model validation.

Despite these limitations in the model, insights were obtained from indicators and the sectors that were excluded from the model when describing the current situation in the Netherlands in Section 5.2. This was aimed at incorporating further insights of the current situation in the region and assist with scenario development and model refinement.

To explore how cement demand might vary under different socio-economic contexts, three scenarios were developed: low, moderate, and high development. Each scenario reflects a distinct level of socio-economic development with varying population growth data and economic development assumptions which in turn shape the development of the other key variables in the model. It is important to note that while the economic development level was not explicitly included as a variable in the forecasting model, it indirectly influences the projections by shaping the structure of other key assumptions. A more detailed description of the developed scenarios and data used in this phase is provided in Section 5.4. Additionally, a sensitivity analysis was conducted to assess the uncertainty in other dimensions such as the one of cement intensity.

5.2 Current Situation

5.2.1 Population and Trends in the Building Stock

The population of the Netherlands has exhibited a consistent upward trend over the period from 2002 to 2023 as shown in Figure 11. In 2002, the population was approximately 16 million inhabitants. This number grew steadily over the years, reaching around 18 million by 2023. In recent years, the population has been increasing more rapidly compared to the previous years. According to PBL Netherlands Environmental Assessment Agency (2024), this rapid growth in recent years is mostly attributed to migration and increased life expectancy. This has provoked a parallel increase in population density, measured as the number of inhabitants per square kilometre. Starting at around 470 inhabitants per km^2 in 2002, the population density saw a continuous rise throughout the period, reaching approximately 530 inhabitants per km^2 in 2023 (PBL Netherlands Environmental Assessment Agency, 2024).

Throughout the same period, the number of total dwellings in the Netherlands followed a similar trend, steadily increasing through the years. In the decade between 2012 and 2022, the Netherlands added 787,866 dwellings to its building stock, with a further 93,771 added in 2023, reaching a total of 9.4 million buildings in 2023. This figure breaks down into roughly 8,2 million dwellings used for residential purposes and around 1.2 million for non-residential purposes. The proportion of residential and non-residential buildings remained stable, with residential buildings consistently representing 87% and non-residential buildings 13% from 2012 to 2023.

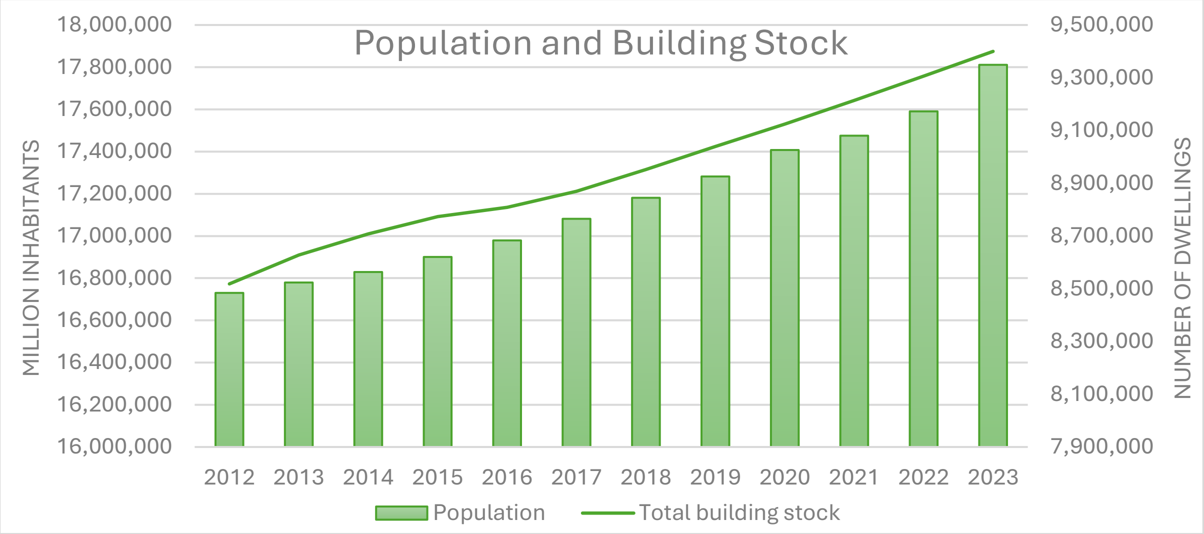

Figure 11: Population (inhabitants) and building stock (number of dwellings) of the Netherlands for the period between 2012 and 2023, as retrieved by PBL Netherlands Environmental Assessment Agency, (2024c), and PBL Netherlands Environmental Assessment Agency (2024a).

5.2.2 Household Stock Trends

Despite the increase in population density, the trend in household sizes in the Netherlands demonstrates a shift towards a growth in one-person households. Figure 12 illustrates the number of households per household size and the average household size between 2002 and 2023. One-person households increased by 42% during this period. Multi-person households, although still prevalent, have seen a relatively slow growth rate compared to one-person households, increasing just by 10% in the same period. This has also led to a decrease in the average household size. In 2002, the average number of residents per household in the Netherlands was estimated at 2.28, steadily declining to 2.11 by 2023.

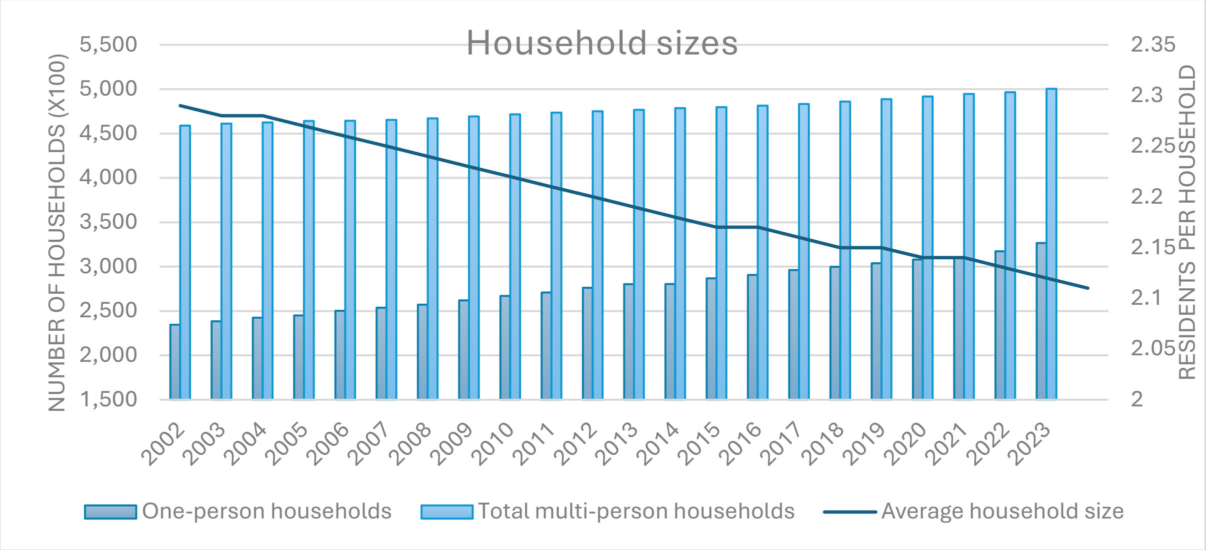

Figure 12: Number of households per household size and average household size between 2002 and 2023 for the Netherlands, as retrieved by PBL Netherlands Environmental Assessment Agency (2024c).

Figure 12**Error! Reference source not found.** visualizes the number of dwellings sold in the Netherlands during the period between 2002 and 2023. With the growth in population density and the growing popularity of one-person households, an upward trend is demonstrated in the number of apartment dwellings sold. However, the greater part of dwellings sold throughout the period remained terraced houses. This is because the majority of residential dwellings in the Netherlands are one-dwelling residences being either terraced, corner, semi-detached, or detached. In 2019, apartment dwellings represented 20.2% of the total dwellings in the Dutch housing stock, with the remaining 79.8% accounting for one-dwelling buildings (Appolloni & D'Alessandro, 2021).

These shifts in household dynamics reflect the changes in response to meeting the evolving needs of the population. According to the Bouwberichten (2024), as of today, most of the residences being constructed are apartments. This indicates a growing trend towards taller buildings. While higher residential buildings are being constructed, more and more inhabitants reside alone. This suggests that the trends towards more one-person households and apartments are more likely to continue in the future, because of increasing population density.

However, in residential building permits, it can be observed in Figure 14 that one dwelling permits in 2023 still hold the highest share, indicating that despite the growing popularity of apartment dwellings, single-unit residential buildings continue to dominate. This suggests that while there is a noticeable trend towards constructing taller buildings and accommodating more one-person households, traditional one-dwellings remain prevalent in residential construction. This dual trend underscores the diversity in housing preferences and the ongoing need to balance between high-density developments and traditional housing types to meet the varied demands of the population.

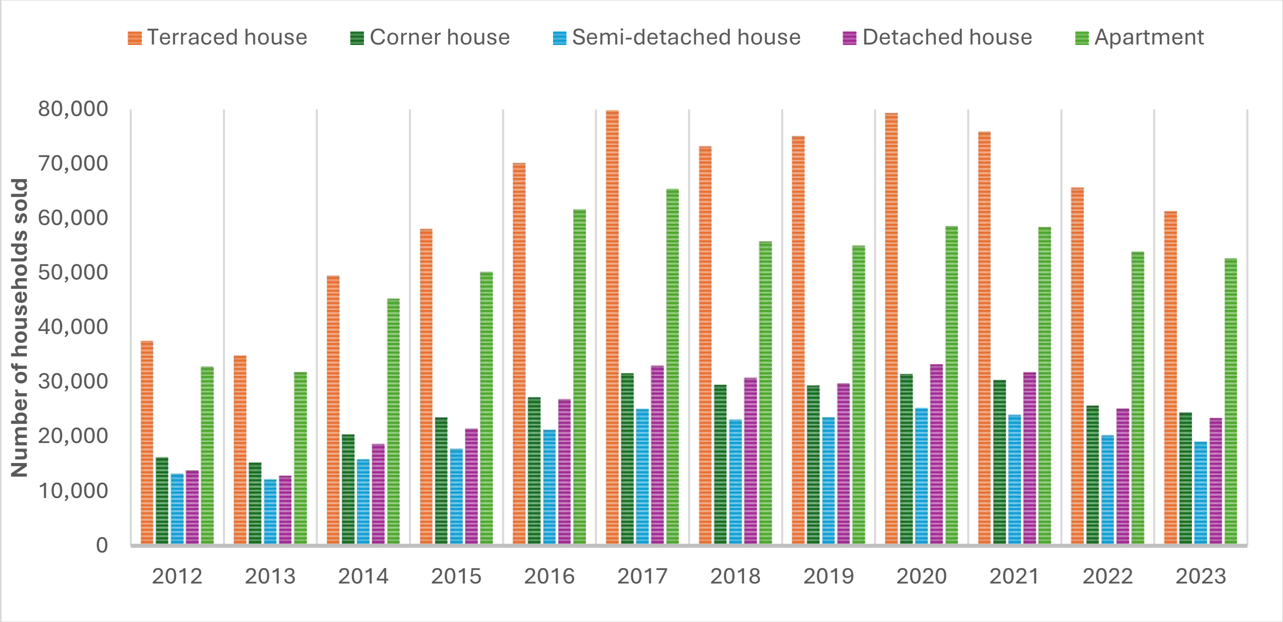

Figure 13: Number of dwellings sold in the Netherlands during the period between 2002 and 2023, as retrieved by PBL Netherlands Environmental Assessment Agency (2024b).

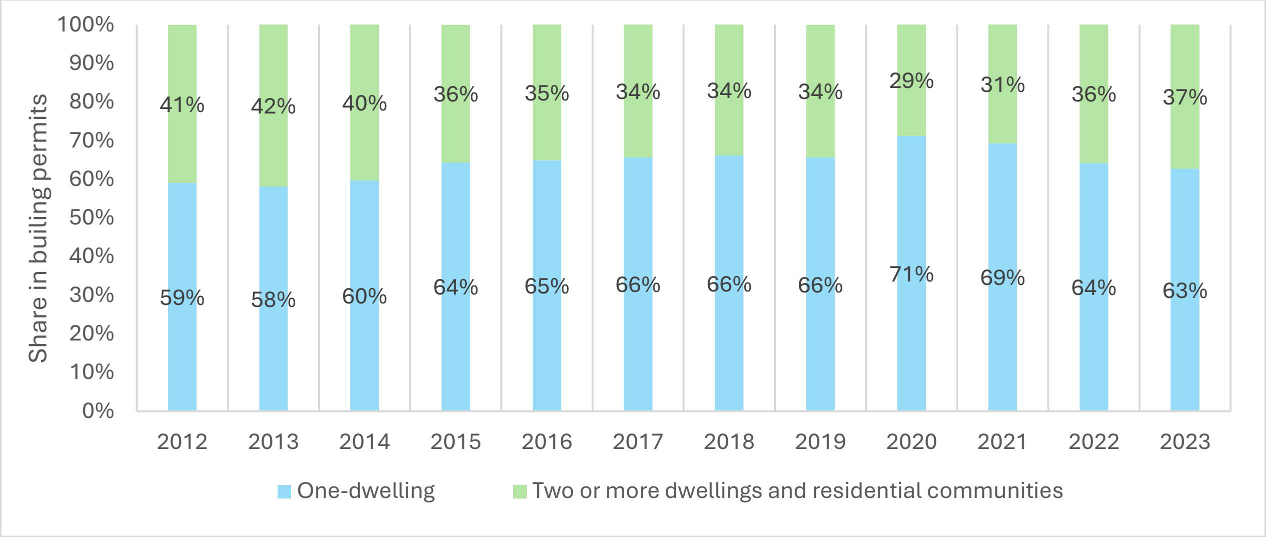

Figure 14: Share of building types in building permits for the Netherlands from 2012 to 2023, as retrieved by PBL Netherlands Environmental Assessment Agency (2022), and Eurostat,(2024b).

Tracking trends in the average dwelling size in square meters for different household types in the Netherlands presents a challenge due to the limited availability of detailed data. However, some reports provide insights into these trends. According to Appolloni & D'Alessandro (2021), the average dwelling size in the Netherlands was estimated to be 106.7 m^2 in 2019. Additionally, in Table 3 a breakdown of average floor areas per dwelling type and vintage level for the Netherlands in 2015 is shown as retrieved from Koezjakov et al. (2018).

Table 3: Average floor areas per dwelling type and vintage level for the Netherlands in 2015, as retrieved by Koezjakov et al. (2018).

Building Type	Floor area for standard, retrofit, and advanced retrofit (m^2)	Floor area for new and advanced new (m^2)
Mid-terrace	106	124

End-of-terrace	106	124
Detached	144	170
Semi-detached	123	148
Apartment	76.7	91.9

From Table 3, it is observed that detached and semi-detached dwellings tend to have larger floor areas compared to terraced dwellings, as well as apartments. Detached houses offer the most spacious living areas, especially in newer constructions, which can reach up to 170 m^2. In contrast, apartments have the smallest average floor areas, with newer apartments averaging 91.9 m^2. These figures provide a snapshot of the current situation in the Netherlands regarding the floor area of dwellings however, there is a significant variability based on the type of dwelling and vintage level. This variability reflects different living preferences, economic conditions and needs amongst the population.

For instance, with the rise in one-person households and apartment dwellings, the average household size in the Netherlands could potentially decline. Conversely, sustained economic growth might drive a preference for more spacious living arrangements, particularly in detached and terraced houses, especially in rural and suburban areas where larger households are more common (Bank of England, 2020). This dual trend highlights the complex interplay between economic conditions, demographic shifts, and housing preferences in shaping demand for different types of dwellings.

5.2.3 Trends in the Non-Residential Sector

Figure 15 illustrates the distribution of various non-residential building functions in the Netherlands from 2012 to 2023. Each bar represents the proportion of different non-residential functions out of the total non-residential buildings in each year. Throughout the years, the largest share in non-residential dwellings has consistently been held by other non-residential dwellings, despite a decrease of approximately 2% in their share in 2023 compared to earlier years. Industrial dwellings maintained the second largest share and experienced a 17% increase during this period, bringing their proportion up to 18% of the total in recent years. Detention buildings held the lowest share, ranging from 0.007% in 2012 to 0.005% in 2023.

Non-residential dwellings with more than one function experienced the largest increase from 2012 to 2023, growing by 39%. Although their share of the total remains low. Recreational and healthcare buildings increased by 25% and 23%, respectively, from 2012 to 2023. The increase in recreational facilities elevated this category to the third largest in 2023. Meanwhile, shops, offices, meeting spaces, and sports facilities maintained relatively stable shares over the years. Finaly, education and detention buildings are the only categories to experience a decrease from 2012 to 2023, declining by 13% and 28%, respectively.

Variability in sizes across different non-residential functions can influence the overall cement demand of non-residential buildings. However, detailed insights into the average size of each non-residential building type are challenging to estimate without specific data. The report of

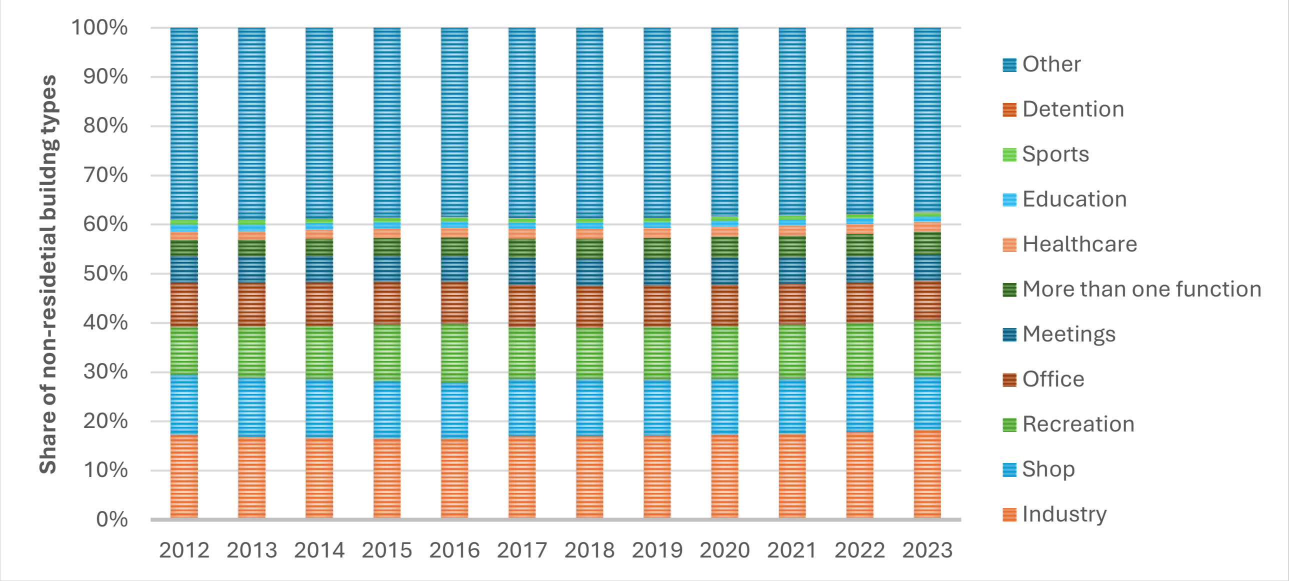

Figure 15: Share of non-residential building types in the Netherlands between 2012 and 2023, as retrieved by PBL Netherlands Environmental Assessment Agency (2024a).

5.2.4 Economy and Construction Activities

Figure 16 offers a closer look at the relationship between the development of GDP and new building constructions in the Netherlands between 2012 and 2023. The economic development in the Netherlands follows an upward trend throughout the period between 2012 and 2023, apart from 2020 when the outbreak of the COVID-19 pandemic heavily influenced the economy. In 2023, the GDP for the Netherlands in 2010 Euro prices was around 776 million Euros, increasing by almost 134 million Euros from 2012. During the same period, new building constructions followed a similar trend to GDP development, indicating a correlation between the two indicators. Notably, new building constructions reached a peak in recent years, as did the GDP indicator. While in 2020, the global reactions to the COVID-19 pandemic also influenced the construction of new buildings in the Netherlands.

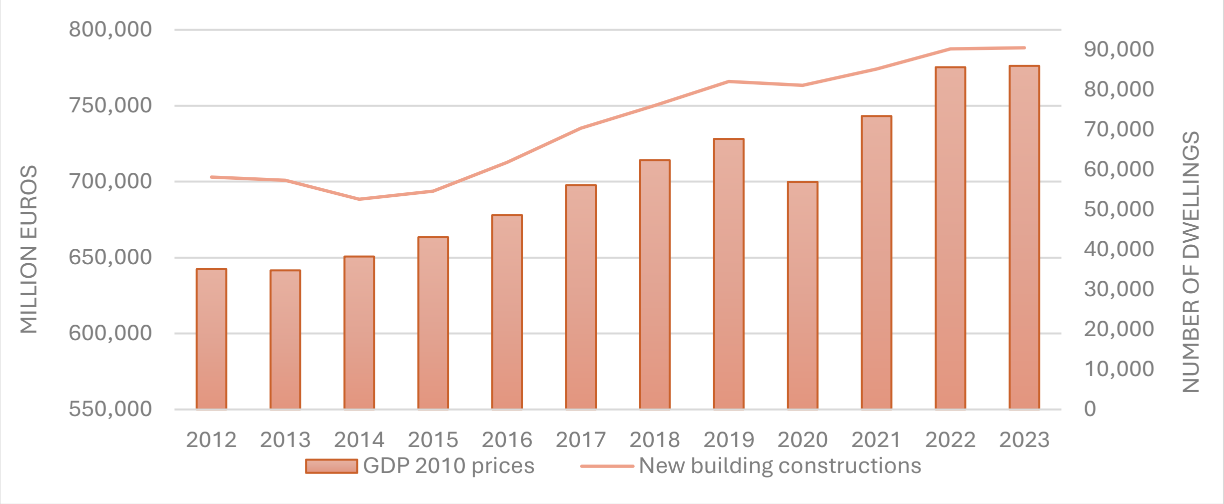

Figure 16: GDP in 2010 prices (million Euros) and new building constructions (number of dwellings) of the Netherlands between 2012 and 2023, as retrieved by Eurostat (2024d) and PBL Netherlands Environmental Assessment Agency (2024a).

Figure 17 visualizes the level of activity in different construction activities of the Dutch building stock. In 2023, roughly 75% of total additions accounted for new constructions. Other additions include renovations, change of utility function, and splitting of dwelling units. While other additions maintained a higher share in total additions in earlier years, their share has decreased since 2015. This emphasizes that new constructions are the main driver of new dwelling units in the building stock of the Netherlands in the latest years.

Furthermore, accurately gauging the level of activity in renovations explicitly poses significant challenges. The amount of cement utilized in renovation projects can vary widely depending on factors such as the scope of the renovation, structural requirements, and the extent of modernization. Unlike new constructions, where cement usage tends to follow predictable patterns based on building type, size, and design, renovations exhibit greater variability in the types and quantities of materials employed. This variability complicates the precise measurement of cement consumption in renovation activities. Therefore, projecting cement demand arising from renovation projects presents significant challenges and was not included in the forecasted results.

Moreover, demolition activities, while maintaining a relatively stable level, they have been slowly decreasing. This trend could potentially indicate a growing popularity towards renovation and retrofitting of existing buildings as an alternative to demolition. However, the activity level of other additions does not reflect a corresponding increase over recent years. This is likely because other additions only capture renovation activities that result in new dwelling units being added to the building stock. Renovations of existing dwellings are not captured by this indicator which makes it even more difficult to account for these types of activities in the model.

Moreover, the stock balance represents the balance between total additions and total withdrawals in the end of a year. Through the period 2012-2023, the stock balance maintained a positive value, indicating that additions consistently outpaced removals. Between 2013 and 2016, the stock balance growth appears to have slowed down, decreasing from around 110,000 new additions in 2013 to around 35,000 in 2016. The dramatic decrease in 2016 can be mainly attributed to an increase in other withdrawals, which grew by 116% compared to the previous year. Since 2018, the stock balance has been observed to gradually return to pre-2016 levels, maintaining a steady but slow growth, except for 2020.

Overall, the Dutch building stock has experienced stable growth with minor fluctuations in recent years, driven predominately by new constructions. As such, in testing the developed framework for projecting cement demand, only new constructions were considered due to their significant contribution to building activity, where cement is most extensively utilized compared to other construction activities.

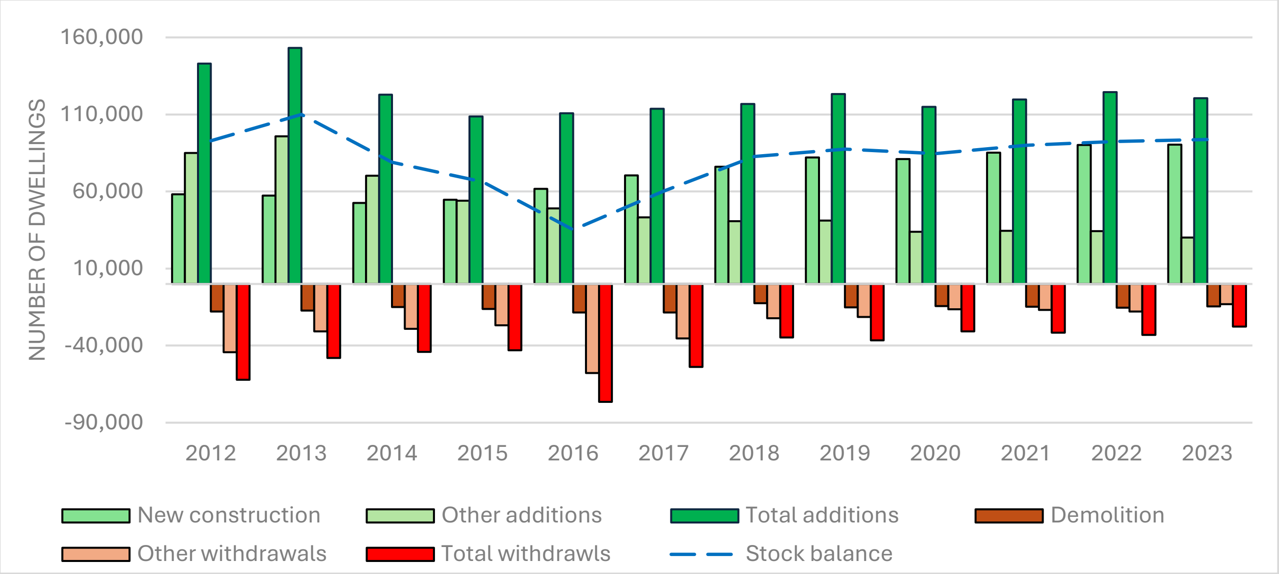

Figure 17: Construction activities in the total building stock and dwellings stock balance of the Netherlands from 2012 to 2023, as retrieved by PBL Netherlands Environmental Assessment Agency (2024a).

5.2.5 Building Permits

Figure 18Figure 18 illustrates building permits by sector and as a total in the Netherlands from 2002 to 2023. Building permits encountered fluctuations over the years, experiencing periods of growth and periods of decline. In recent years, a downward trend has been observed in building permits. Notably total building permits declined by 30% from 2021 to 2023, dropping from 23.83 million m^2 of permitted building area to 16.74 million m^2. This decrease is mostly attributed to the drop in residential building permits during this period, contributing 73% to this decrease. Residential building permits declined by 17% in 2022 compared to the previous year, and a further 26% in 2023. Non-residential building permits followed a similar pattern with fewer fluctuations and a slower rate of decline. The significant decline in building permits of the latest years is expected to impact the production of new dwellings in the near future and has caused significant concern within the industry. Experts fear a substantial drop in housing production in the coming years (Bouwberichten, 2024), while the EIB estimates that around 12,000 full-time jobs could disappear between 2024 and 2025. Although, a recovery in employment is foreseen in the medium term (Bouwberichten, 2024).

Figure 18: Total, residential, and non-residential building permits in the Netherlands from 2002 to 2023, as retrieved by PBL Netherlands Environmental Assessment Agency (2022), and Eurostat,(2024b).

When studying the relationship between the total BPI and the total activity level in new construction of buildings, the data reveals that a one-year time lag between these two indicators shows a stronger correlation than when no time lag is applied. Figure 19 visualizes the total amount of BPI in all types of buildings for the period between 2012 and 2022 along with the activity level of new constructions for all types of buildings for the period between 2013 and 2023. The data demonstrates that changes in BPI are closely followed by corresponding changes in new construction activity after one year. For instance, a dip in the BPI around 2013 is followed by a dip in new constructions in 2014. Similarly, an increase in the BPI starting from 2014 is mirrored by an increase in new constructions in 2015. When analysing the data without a time lag, the correlation between those indicators is less apparent. This suggests that the BPI serves as a leading indicator, providing an advance signal of future construction trends.

When analysing the relationship between BPI and activity level in new construction for the residential and non-residential sectors separately, it is observed that residential BPI correlates better with the number of new buildings constructed in the following year, while for the non-residential buildings, a two-year lag is more accurate.

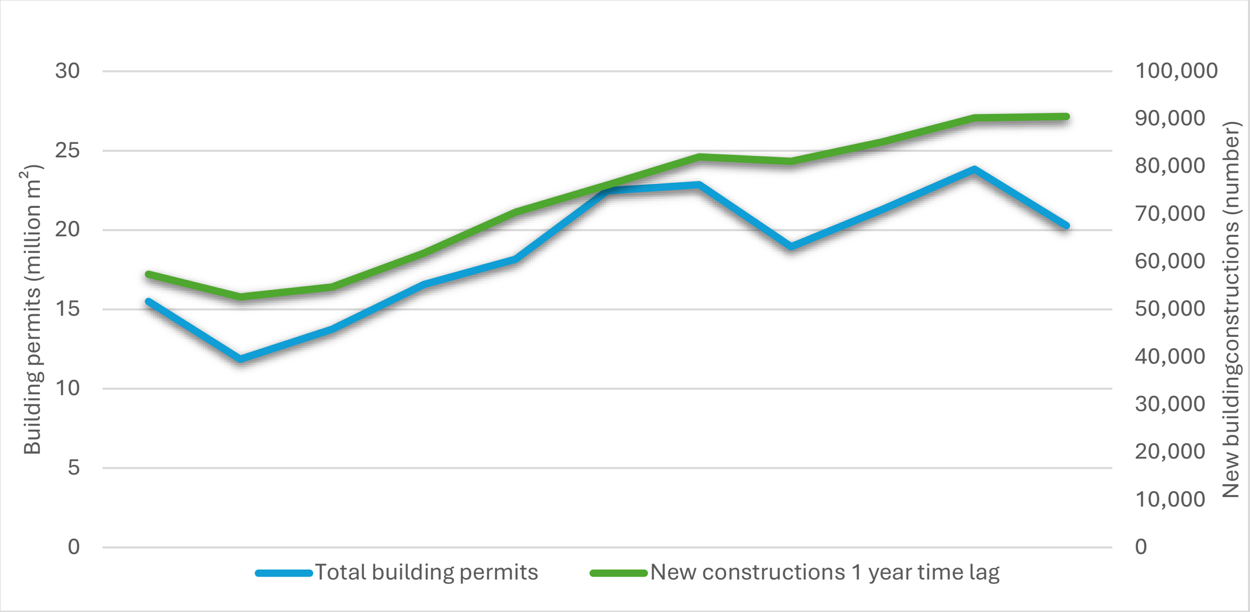

Figure 19: Total building permits from 2012 to 2023 and new building constructions from 2013 to 2023 for the Netherlands, as retrieved by PBL Netherlands Environmental Assessment Agency (2022), Eurostat,(2024b), and PBL Netherlands Environmental Assessment Agency (2024a).

5.2.6 Civil Engineering Sector

Figure 20 shows the GVA in construction excluding specialized activities together with the share of the building and civil engineering sectors from 2005 to 2023. Specialized activities were excluded from this total to enable a more accurate comparison in relation to cement demand, as these activities, such as interior finishes, electrical works, and plumbing installations, may not directly impact cement demand but involve other specialized materials.

The share of the civil engineering sector has shown a generally upward trend over the period analysed. Starting at 25% of the construction GVA, it increased to 34% by the end of the period, despite fluctuations. The sector has seen a steady increase in infrastructure and renewable energy projects, with the Dutch government investing heavily in transport network projects. In 2023, the budget allocation for infrastructure was approximately 4 billion Euros (Research and Markets, 2024). This includes substantial investments in railway improvements, road construction, water management, and waterways (Research and Markets, 2024).

The emphasis on civil engineering projects is evident from the rise in the share of the civil engineering sector in the construction GVA. This sector's growth is driven by government commitment to infrastructure development and large-scale public works. Additionally, the construction value added rose by 2.1% year on year in the third quarter of 2023, reflecting the sector's resilience and growth (Research and Markets, 2024). This increase highlights the sector's ongoing strength and its crucial role in the broader economy.

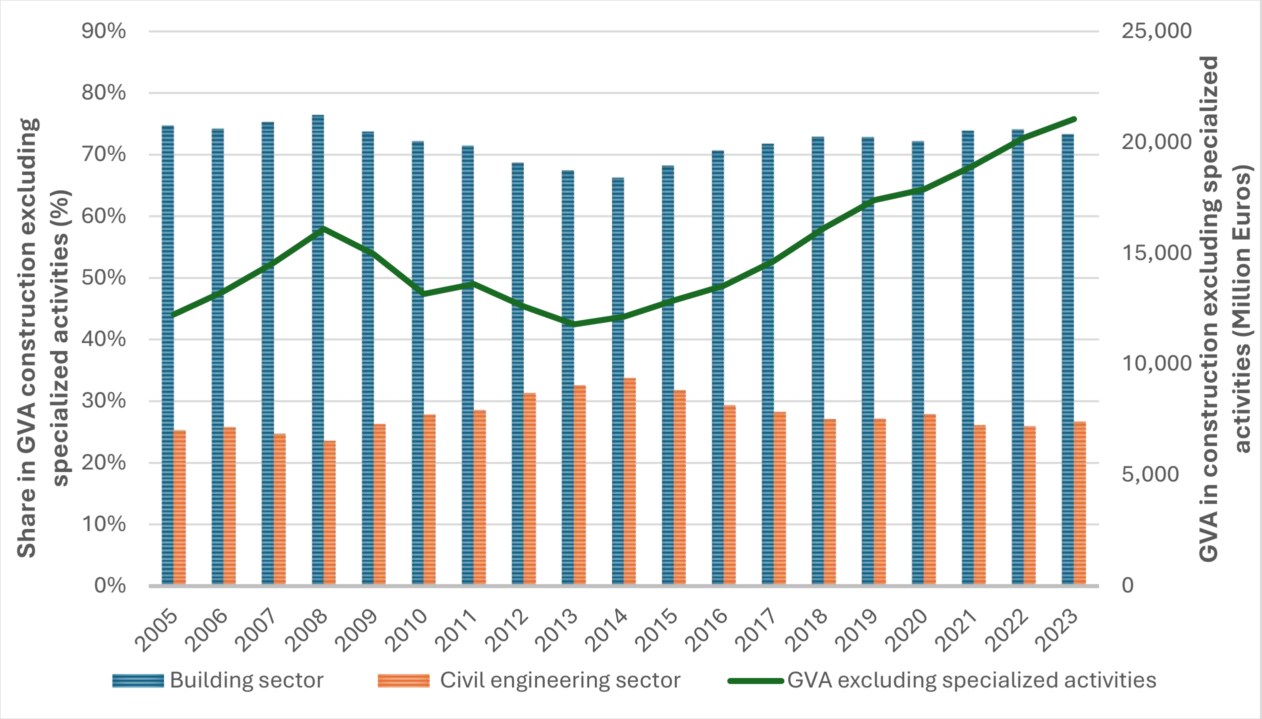

Figure 20: GVA in construction (in million Euros current prices) excluding specialized activities and share of the building and civil engineering sectors in this total from 2005 to 2023 for the Netherlands, as retrieved by Eurostat, (2024e).

5.2.7 Cement Intensity

The Netherlands produces around 2 million tonnes of cement per year. The country's cement production process is characterized solely by grinding imported clinker, as domestic clinker production ceased entirely with the closure of the only clinker production facility in 2020. Consequently, Dutch cement production sites rely entirely on imported clinker. On top of that, a considerable portion of the country's cement demand is met through cement imports, primarily from other EU countries. For instance, in 2019, approximately 54% of the Dutch cement consumption was imported. This situation underscores the challenges and dependencies within the Dutch cement sector, shaped by the cessation of local clinker production and a reliance on external sources to meet domestic demand. While the framework developed in this study for projecting cement demand does not explicitly incorporate cement supply dynamics, understanding the supply side is crucial as it establishes the types of cement utilized in the country, thereby influencing the composition and structural integrity of concrete structures.

Dutch cement production primarily focuses on manufacturing two main types of cement, namely CEM III and CEM I. CEM I, also known as Portland cement, is a basic type of cement consisting primarily of clinker and is widely used in general construction due to its versatility and strength properties (Xavier & Oliveira, 2021). CEM III, on the other hand, is a blend of clinker and blast furnace slag or fly ash, designed to enhance durability and sustainability in construction applications. These types of cement also dominate the imports into the Netherlands, reflecting the country's preference and demand for them (Xavier & Oliveira, 2021).

In terms of domestic consumption, approximately 50 to 60% of cement used in the Netherlands is CEM III, which aligns with its benefits for sustainable construction practices (Xavier & Oliveira, 2021). CEM I constitutes around 35% of the market share, while CEM II, a blended type of cement similar to CEM III but with different SCMs, makes up the remaining 5 to 15% based on market conditions and specific project requirements (Xavier & Oliveira, 2021). This distribution reflects the Dutch cement industry's strategic approach to meeting varied construction demands while prioritizing sustainability and environmental considerations.

The choice of cement type significantly influences the composition and performance of concrete structures (European Cement Association, 2023a). Concrete made with CEM I typically features higher cement content compared to concrete using CEM III (Ajumobi, 2020). This higher cement content is necessary to achieve specified performance requirements and ensure durability in various applications such as high-rise buildings, bridges, and infrastructure projects where structural integrity is paramount. In contrast, CEM III allows for reduced cement content while maintaining comparable or even superior performance characteristics (Ajumobi, 2020). This is due to the pozzolanic or latent hydraulic properties of SCMs, which contribute to the strength and durability of concrete over time.

As a result, concrete structures utilizing CEM III can achieve similar compressive strengths and long-term durability as those using CEM I, despite a lower overall cement content. According to Kermeli et al. (2011), the average cement content in concrete structures ranges between 10% and 15%. Concrete structures utilizing CEM I, often fall towards the higher end of this range, closer to 15%, to meet stringent strength and durability criteria, while CEM III concrete structures can achieve comparable results with a cement content that may range from 10% to 12% (Szcześniak et al., 2020).

Furthermore, a report from Sprecher et al. (2021), analyses material intensities of the Dutch building stock, including concrete, by collecting data from buildings being demolished in the Netherlands. Table 4Table 5 presents the concrete intensity of different building types in the Netherlands. Since these data are retrieved from demolished buildings, they may not accurately reflect the cement intensities of new building structures. However, they provide valuable insights into the historical use of concrete across different building types. Additionally, the study by Sprecher et al. (2021) reveals that the concrete intensity of apartment buildings is significantly higher compared to the findings of Koezjakov (2017), which indicated lower concrete intensity for apartments relative to row houses. This research aligns with Sprecher et al. (2021) in considering the higher concrete intensity of apartments due to their comprehensive dataset that captures detailed variations in concrete use across building types, providing a more nuanced understanding of material intensities. However, it acknowledges this alignment as a limitation in data granularity.

Table 4: Concrete intensity of different building types in the Netherlands, as retrieved by Sprecher et al. (2021).

Building type		Concrete intensity (kg/m2)
Residential function	Row	353.2
	Single	974.1
	High rise	699.5
	Apartment	883.1
	Average	727
Non-residential function	Offices	676.6
	Commercial	634.4
	Other	625.6
	Average	646

5.3 Model Development and Evaluation

To capture regional variations in cement consumption, the model adopts a bottom-up approach that translates activity within end-user sectors into a physical measurement of cement demand. This approach is similar to the one established in the China Energy and Emission Paths to 2030 model (Fridley et al., 2011), where specific cement intensity factors are considered for different end-user sectors to estimate demand. End-user indicators measure the quantity of construction activity of a project type in physical terms, while cement intensity factors indicate the average amount of cement required per unit of activity. Furthermore, the model includes a top-down approach that incorporates socio-economic assumptions and data, directly and indirectly, to project the development in end-user activity and cement intensity.

Table 5 lists the essential indicators for implementing the developed framework. While these quantifiable indicators provide a robust foundation, it is crucial to acknowledge the influence of qualitative factors, such as the regional policy landscape and structural changes in both the construction and cement industries, as these factors can significantly impact cement demand over time. To account for these dynamics, incorporating expert opinions, case studies, and scenario analysis can help to assess the potential future developments and their implications for the cement market.

Table 5: Indicators for implementing the developed framework for cement demand forecasting, with the included indicators in the model marked with an "X" in the third column.

Indicator	Unit	Included in the model
Population projections	inhabitants	X
Population density	Inhabitants per km^2	
Age distribution of the population	%	
GDP	Euros	
Interest rates	%	
Rental rates and property values	Euros	
Government spending on civil engineering works	Euros	
Construction GVA per sector	Euros	
Building stock per sub-sector	Number	X (only for residential)
Share of building types per building sub-sector	%	X (only for residential)
Household size	Number of occupants per household	
New building constructions	Number	X (only for residential)
Renovations/Retrofitting/Adaptive reuse of buildings	Number	
Demolition of buildings	Number	
Buildings lifetime	Number of years	
RCA utilization rate	%	
Floor surface area of construction activities	m^2	X (only for new constructions))
Average floor areas of building types	m^2	X
Average floor areas for different vintage levels of building types	m^2	
Concrete intensity per building type	kg/m^2	X
Cement content in concrete structures	%	X

Cement intensity	kg/m^2	X

5.3.1 Modelling Steps

Population projections in the model shape the future development of the residential building stock in the country under study. Population forecasts can be sourced by various demographic studies, national statistical offices, and international organizations. The model assumes linear growth of the residential building stock in correlation with the population projections. To achieve this, a linear regression is applied in this analysis. Linear regression is a statistical method used to model and analyse the relationship between a dependent variable, which in this case is the residential building stock we aim to predict, and an independent variable, which is the population forecasted data used to make these predictions. This analysis utilizes historical data of the dependent and independent variables to determine two key components: the slope, and the intercept. The slope quantifies how much of the building stock is expected to increase with each unit increase in population, while the intercept indicates the baseline amount of the building stock in the absence of population growth. The growth factor is applied to refine the model's accuracy further. This relationship is captured by Equation 6.

$$Residential\ building\ stock\ (num.) = (Population * \ Slope * Growth\ Factor) + Intercept$$

Equation 6

In the case of acquiring specific data for average floor surface areas of the non-residential sector, the residential building stock in Equation 6 can be replaced with the total building stock, to project the development of the total building stock. Subsequently, the total building stock can be divided into residential and non-residential stock by assuming specific shares for each category. This assumption can be based on historical development patterns and current trends in construction practices, ensuring that the model reflects realistic proportions for the short term. For the long-term, these shares can be adjusted over time to account for changing urban landscapes and shifts in economic activities, providing a more accurate representation of future building stock distribution. By multiplying these shares with the total building stock, the number of buildings in the residential and non-residential sectors can be estimated.

The next step in the model involves assessing the activity level of new constructions. This indicator represents the share of newly constructed buildings within the respective building stock. For instance, a 1% share means that 1% of the building stock is newly constructed. Higher shares suggest increased construction activity, influenced by both economic conditions and population growth. High economic growth provides resources for constructing new buildings, while a growing population necessitates additional construction. Conversely, low population growth and economic development result in reduced construction activity in the model. By multiplying these shares with the respective building stocks, the model projects the number of newly constructed buildings in each sector annually.

To convert the number of newly constructed buildings in a year into a physical measurement for the floor surface area for each building type (bt) that is constructed, Equation 7 is utilized. The successful implementation of this equation requires accurate data on the average floor surface area of different building types and an assumption for the share of each building type in the respective building stock (residential or non-residential). This allows for a detailed disaggregation of building types in the model. To quantify the share of each building type in the model, socio-economic factors, and regional characteristics are incorporated. For the residential sector, this includes variables such as population growth, land availability, and possibly historical preferences in the region. For instance, high population growth coupled with limited land availability may lead to an increase in apartment dwellings and high-rise buildings to accommodate the growing population within constrained space. Conversely, in areas with lower population growth and ample land, single-family homes might be more prevalent.

For the non-residential sector, the model can incorporate factors such as the demographics of the population, particularly age distribution, and the structure and growth patterns of the regional economy. For example, if the population is predominantly older, there may be a greater need for healthcare facilities to address the specific needs of this age group. Additionally, if the local economy is expanding with a focus on technology and innovation, there might be a higher demand for office spaces and tech-related infrastructure, rather than traditional retail or industrial buildings.

Furthermore, to account for the period required to complete building construction projects, Equation 7 implies that the number of new building constructions in a year determines the new floor surface area in the next year. This assumption about the time difference can be informed by analysing historical construction timelines in relation with permit issuance, ensuring that the model aligns with actual project completion times.

$$New\ floor\ surface\ area_{year\ X_{bt\ i}}\,(m^2) = \left(New\ constructions_{year\ X-1}(num.) * share\ in\ building\ stock_{bt\ i}(\%)\right) * average\ floor\ area_{bt\ i}\ (m^2)$$

Equation 7

The next step in the model is to quantify the cement intensity of each building type for the region of study. Acquiring data on concrete intensity and then assuming a share of the cement content in concrete structures to estimate cement intensity, enables further disaggregation in the model. This implies that cement intensity can vary over time, influenced by changes in cement content due to technological advancements in the construction and cement industries. Therefore, Equation 8 is used to estimate cement intensity in the model. Existing research and industry reports analysing data from actual construction projects within the region of study can provide a solid foundation for estimating average cement intensity factors. Collaboration with local construction companies and industry experts can also yield valuable insights into regional construction practices and cement usage.

$$Cement\ intensity_{bt\ i}(kg/m^2) = concrete\ intensity_{bt\ i}\ (kg/m^2) * cement\ content\ in\ concrete\ (\%)$$

Equation 8

The final step in the model is to multiply the floor surface area of each building type by the respective cement intensity to estimate cement demand from the buildings sector, as shown in Equation 9.

$$Cement\ demand_{building\ type}\ (kg) = New\ floor\ surface\ area_{buiilding\ type}(m^2) * Cement\ intensity_{building\ type}(kg/m^2)$$

Equation 9

5.3.2 Model Validation

The validation of the model with historical data is crucial for understanding its accuracy and reliability. By comparing the modelled cement demand to the actual cement demand, we can assess how well the model captures real-world dynamics and identify any discrepancies. Therefore, the model was initially tested using historical data of the BPI for the Netherlands and the cement intensities as retrieved from Sprecher et al., (2021) to estimate cement demand from the building sector. Figure 21 shows the modelled cement demand, calculated using Equation 9, together with the actual cement demand of the Netherlands as calculated in Chapter 2.

The actual cement demand includes all end-uses of cement, encompassing both building and civil engineering sectors, while the modelled demand only considers the buildings sector. The cement demand attributed to the civil engineering sector was not modelled in this case study due to the limited available data and because the building sector represents a larger share of total cement demand. Despite this limitation, the model closely follows the actual demand trend, highlighting that building sector activities significantly influenced overall cement demand during the study period.

In 2007, the modelled cement demand was the only year surpassing the actual demand. In 2008, the modelled demand was only 1.4% lower than the actual cement demand. These two years recorded the highest BPI from 2002 to 2021. Considering the onset of the global economic recession in 2008, it is plausible that while building permits were issued, economic constraints during that challenging period led to delays in the construction of buildings. Consequently, the actual cement demand was slightly lower than anticipated due to postponed or slowed construction activities.

This suggests that the model is reasonably accurate in reflecting trends in the building sector. However, it also highlights the sensitivity of construction activities to broader economic conditions. The delays and reduced construction activity during the recession indicate that the actual use of cement can be influenced by economic factors that impact the pace of construction projects, even if permits have been issued. This underscores the importance of considering economic conditions in demand forecasting models to account for potential disruptions in construction timelines and corresponding material usage.

Furthermore, in 2013, the modelled demand exhibited the largest discrepancy from the actual cement demand, underestimating it by 55%. In the same year, the civil engineering sector's share of the GVA in construction, excluding specialized construction activities, accounted for 33%, which was the second-highest share of the sector after 2014. This highlights the substantial role of civil engineering projects in cement consumption that year. The pronounced difference between the modelled and actual demand underscores the model's limitation in capturing the bordered scope of cement consumption. It illustrates how the high level of infrastructure activity can lead to a considerable underestimation of total cement demand when only the building sector is considered in the model.

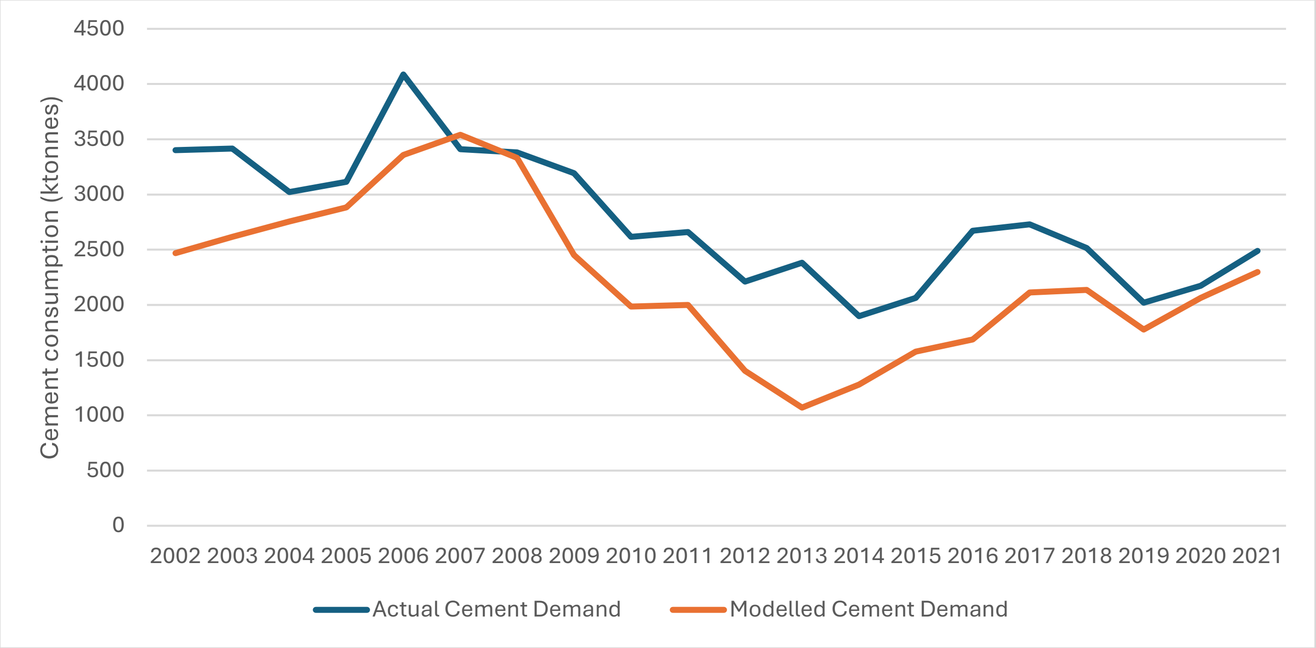

Figure 21: Actual cement demand VS modelled cement demand, as calculated in this study

5.4 Scenario Analysis

5.4.1 Scenario Assumptions

Three distinct socio-economic scenarios have been developed to examine how varying levels of economic growth and population dynamics influence cement demand across the building sector. These scenarios: low development, moderate development, and high development offer insights into how different socio-economic contexts can shape future cement requirements. The scenarios consider only the residential sector due to the limitations mentioned in Section 5.1.

Population forecasts from the PBL Netherlands Environmental Assessment Agency (2024b) informed population growth in the developed scenarios. These forecasts encompass both a point forecast, representing the most likely growth trajectory based on their assumptions, and surrounding 95%, and 67% confidence intervals. The forecasts assume specific future trends concerning births, deaths, immigration, emigration, and household shifts such as divorces. However, a detailed description of how these assumptions are incorporated into the forecasted results is not publicly available. The point forecast, referred as the expected growth scenario, indicates the expected population size and composition if these trends and assumptions hold true. The confidence intervals provide a range of possible outcomes, reflecting the inherent uncertainty in predicting future demographic changes. The lower limit of the 95% forecast interval represents a more conservative estimate where growth is slower than expected. Conversely, the upper limit of the 95% forecast interval represents an optimistic estimate where growth is faster than anticipated. These intervals help to understand the potential variability in population projections and allow for planning under different likely future conditions.

Figure 22 illustrates the population projections, indicating the level of population growth in each scenario. The evolution of the residential building stock in each scenario followed a linear trajectory in accordance with these population projections.

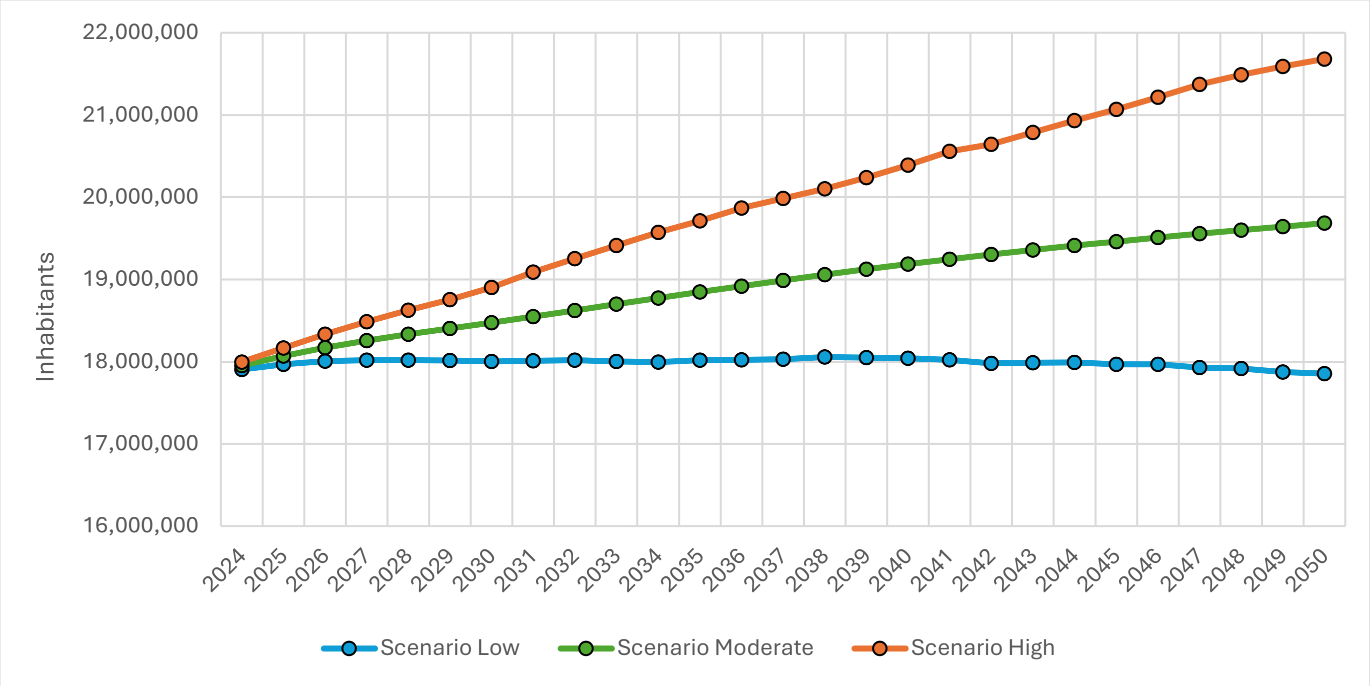

Figure 22: Population projections for the Netherlands from 2024 to 2050, as retrieved by PBL Netherlands Environmental Assessment Agency (2024e).

Furthermore, the types of households being constructed in each scenario were influenced by the level of population growth, with a growing population requiring more two-or-more dwellings to accommodate the increasing demand. Figure 23 illustrates the shares of household types assumed in each scenario.

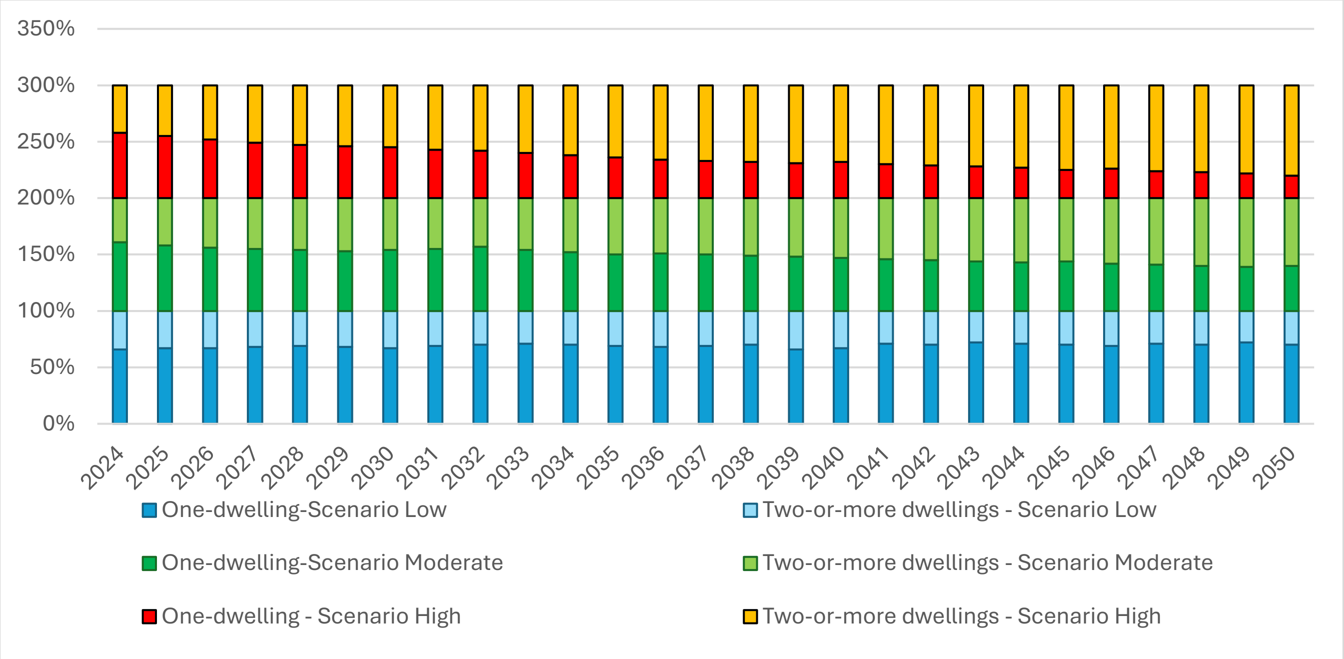

Figure 23: Share of household types assumed for each scenario from 2024 to 2050.

The assumptions for the level of new construction activity are incorporated in the model depending on the health of the economy. In the scenario with robust economic growth, higher construction activity is expected, reflecting increased investments. Conversely, in the scenario with limited economic growth, new construction activity is anticipated to be lower, as economic constraints reduce investment and development. In the scenario with moderate economic growth, construction activity is projected to experience a balanced increase, accommodating a steady rise in demand for new constructions without reaching the high levels seen in the scenario with robust economic growth. The number of new residential building constructions for each scenario can be found in Figure 24.

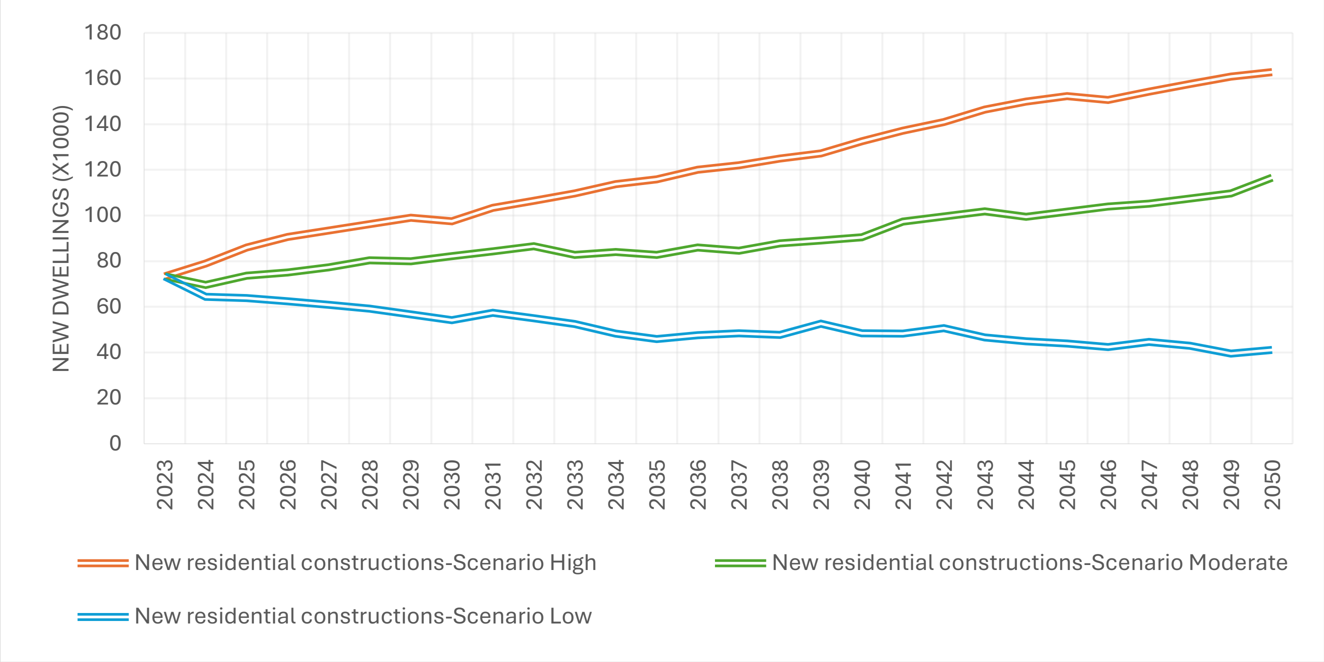

Figure 24: New residential building constructions in each scenario from 2024 to 2051.

To account for variations in average floor areas and cement intensities, different periods were considered for the forecast period. The first period encompasses historical trends of cement intensity and average floor areas and extends until 2025, with uniform values applied across all three scenarios. Following this period, the variables are adjusted based on the specific characteristics of each scenario, reflecting changes in economic growth. Moreover, in the model, one-dwellings include single households, while two-or-more dwellings are the average between apartments and row houses. This assumption applies to both the average floor area and concrete intensity variables.

Table 6 illustrates how average floor areas for one-dwellings and two-or-more dwelling units are expected to change throughout the forecast period in each scenario. Economic conditions determine the extent of these changes, with higher economic growth leading to larger average floor areas due to increased affordability and demand for more spacious living conditions.

Table 6: Average floor areas as assumed in each scenario.

Average Floor Areas (m^2)						
Period	Scenario Low		Scenario Moderate		Scenario High	
	One-dwelling	Two or more dwellings	One-dwelling	Two or more dwellings	One-dwelling	Two or more dwellings
2012-2025	141.7	83.2	141.7	83.2	141.7	83.2
2026-2030	140.7	82.5	142.0	83.6	142.5	84.2

2031-2040	139.6	81.9	142.3	84.1	143.1	84.9
2041-2050	138.3	81.2	143.0	84.8	144.3	85.8

Cement content in concrete structures is also influenced by economic development, with higher growth leading to investments in technology that reduce cement content. In Scenario Low, it is assumed that low economic growth results in no change in cement content, while in the other two scenarios, cement content decreases over time. During the forecast period, concrete intensities were kept constant, as per Sprecher et al. (2021), with 974.1 kg/m^2 for one-dwelling units and 618.1 kg/m^2 for two-or-more dwelling units. Table 7 illustrates the changes in cement content and intensity across all three scenarios.

Table 7: Cement content in concrete structures and cement intensities across scenarios.

Period	**Cement content (%)**	**Cement intensity (kg/m^2)**	
		One-dwelling	**Two or more dwellings**
2012-2025	12.5	121.8	77.3
Scenario Low			
2026-2030	12.5	121.8	77.3
2031-2040	12.5	121.8	77.3
2041-2050	12.5	121.8	77.3
Scenario Moderate			
2026-2030	12.3	119.8	76.0
2031-2040	11.9	115.9	73.6
2041-2050	11.3	110.1	69.9
Scenario High			
2026-2030	11.9	115.9	73.6
2031-2040	11.2	109.1	69.2
2041-2050	10.7	104.2	66.1

5.4.2 Scenario Projections

The main projection results of these scenarios are the new residential floor surface area per year and building type, and cement demand attributed to the residential building sector of each scenario. Figure 25 illustrates the evolution of new floor surface areas per residential building type in each scenario, while Figure 26 shows the total new residential floor surface areas across the developed scenarios. Furthermore, Figure 27 presents the estimated cement demand as projected for all three scenarios.

In 2024, Scenario Low achieves the highest floor surface areas compared to the other two scenarios. This outcome is primarily due to the time lag incorporated in Equation 7 and the high proportion of one-dwelling units in Scenario Low. One-dwelling units, which have a larger average floor area compared to two-or-more dwelling units, significantly contribute to the increased floor surface areas. Additionally, the projected new residential floor surface areas in 2024 are based on the number of new residential constructions from 2023, which is consistent across all three scenarios. As a result, Scenario Low demonstrates the highest floor surface area in 2024. However, the decreasing population in Scenario Low leads to a gradual reduction in the floor surface area of residential buildings over time, which is projected to reach 4.79 million m^2 by the end of the forecast period. Consequently, the projected cement demand of Scenario Low follows a decreasing trend, with fluctuations influenced by changes in new residential floor surface areas. By the end of the forecast period, Scenario Low is expected to demand 540.23 ktonnes of cement for its residential building sector.

In Scenario Moderate, although the share of two-or-more dwelling units surpasses that of one-dwelling units, as shown in Figure 23, the projected floor surface areas of one-dwelling units remain predominant, as can be observed in Figure 25. This is due to the larger average floor area of one-dwelling units. The total residential floor surface area of Scenario Moderate increases over time because of the high share of one-dwelling units and the increasing population, reaching 11.85 million m^2 by the end year of the forecast period. This led to higher cement demand compared to Scenario Low, with a projected consumption of 1079.65 kttonnes by the residential sector in the end year of Scenario Moderate.

Finally, Scenario High achieves the highest new residential floor surface area and cement demand compared to the other two scenarios. The rapid population growth leads in this scenario contribute to the overall increase, but the high share of two-or-more dwelling units limits the extent of increase in new floor surface area over the years, reaching 15.26 million m^2 by the end year of the forecast period. Additionally, while Scenario High demands the most cement for its residential building sector, the difference compared to Scenario Moderate is not substantial. This is due to the higher proportion of two-or-more dwellings, which have a lower concrete intensity than one-dwelling units, and the decreasing cement content over time. By the end of the forecast period, Scenario High is expected to consume 1182.99 ktonnes of cement.

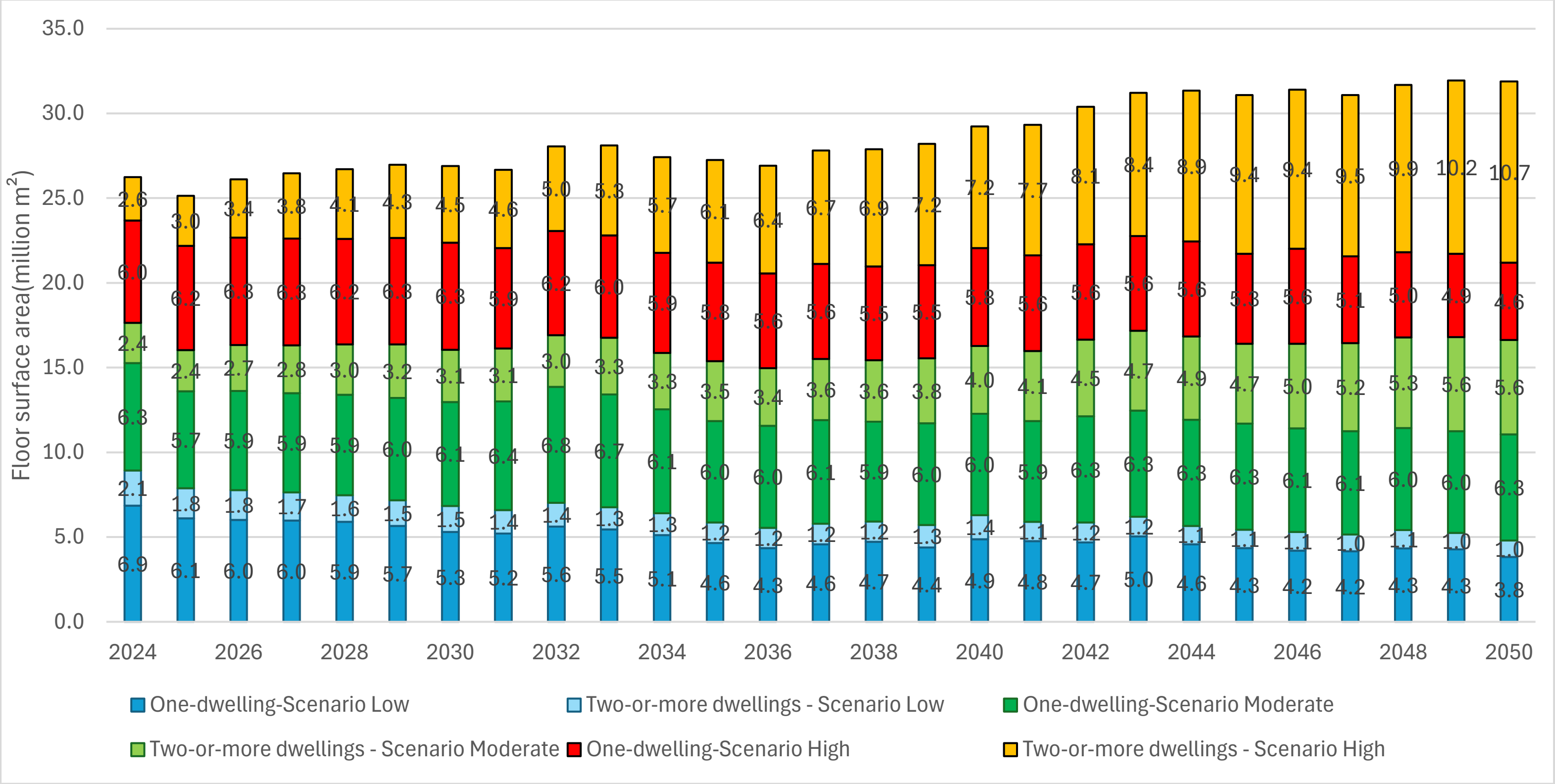

Figure 25: New residential floor surface areas for one-dwelling and two-or-more dwelling units in each scenario.

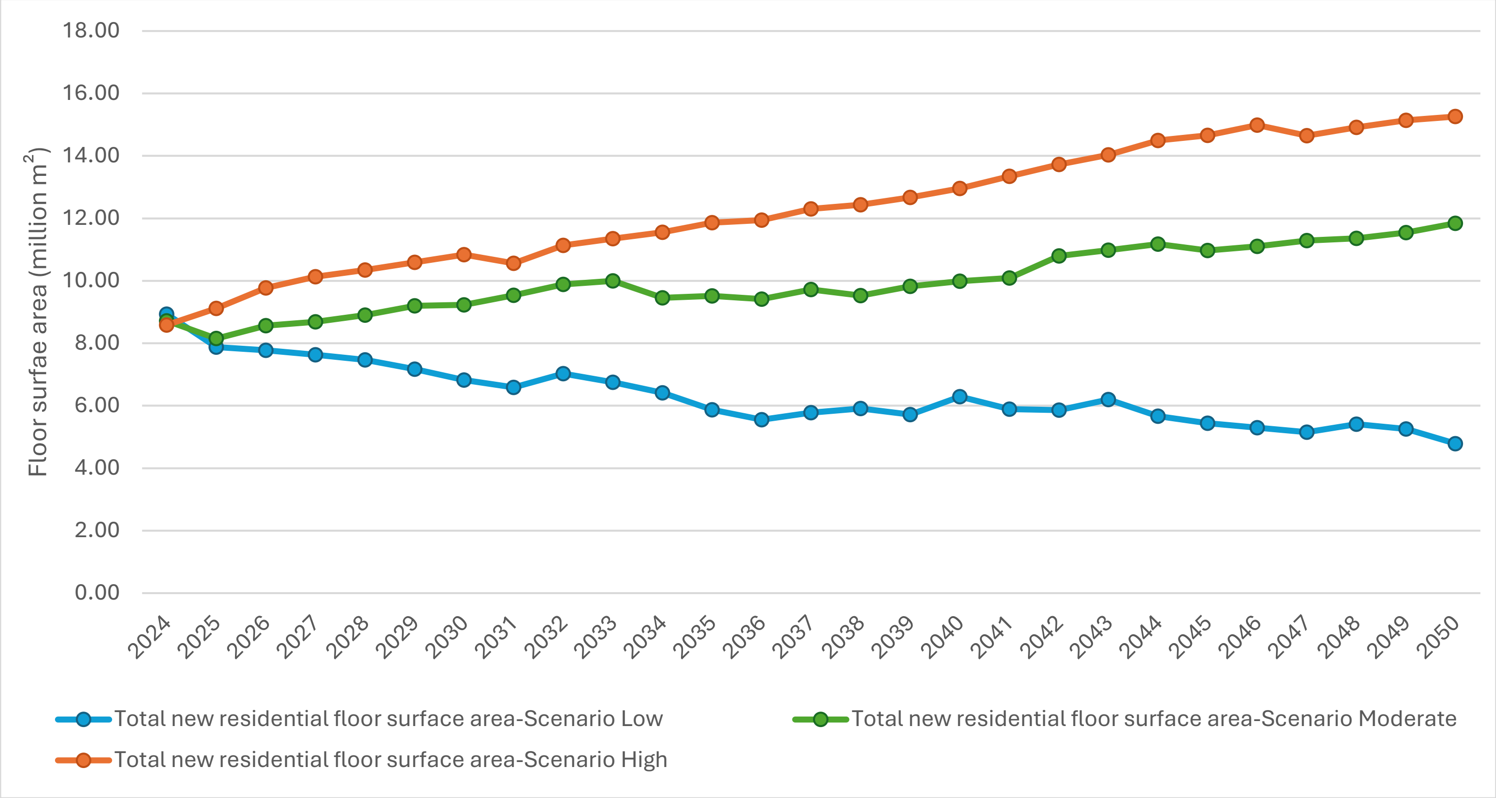

Figure 26: Total new residential floor surface areas across scenarios

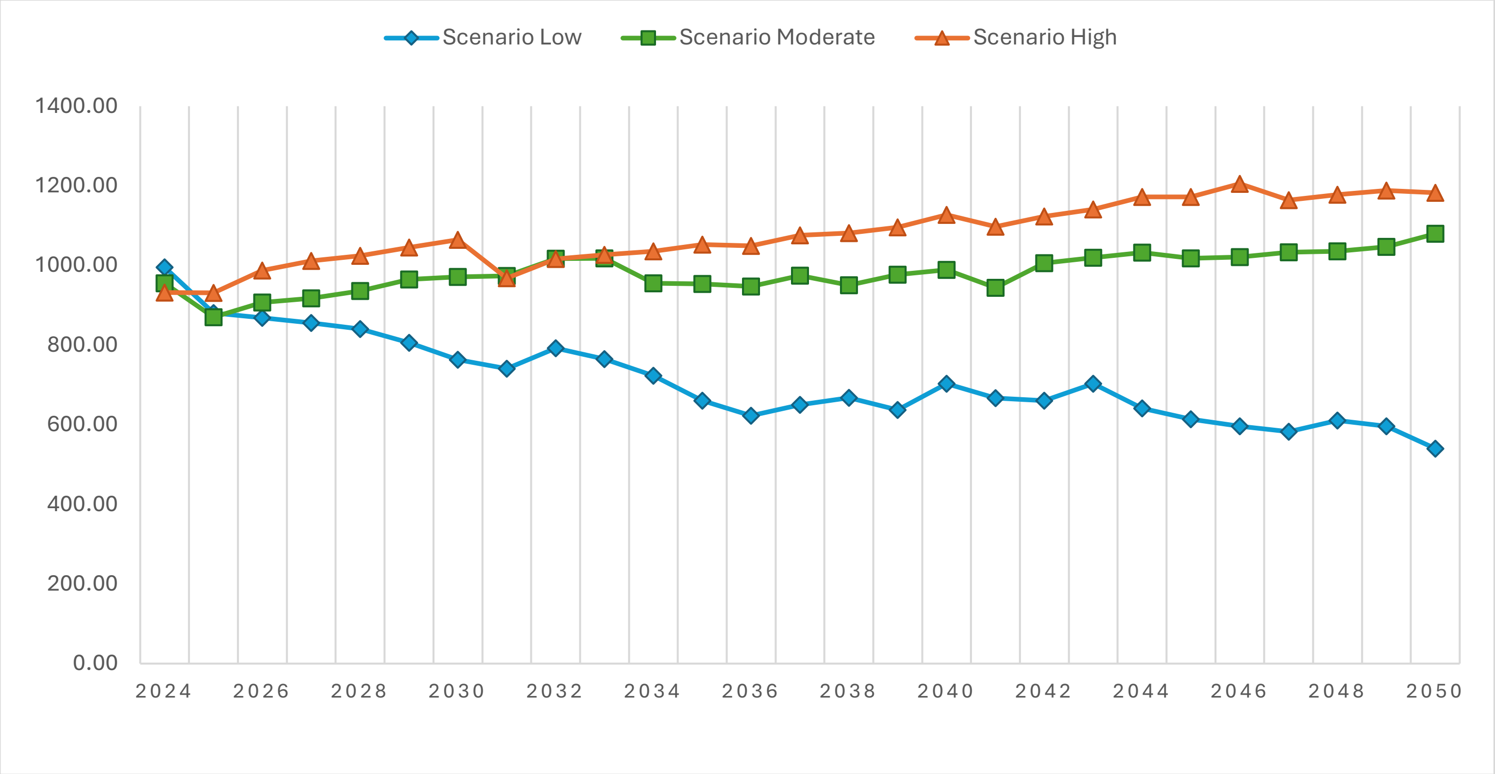

Figure 27: Cement demand attributed to the residential building sector, as projected for each scenario

5.4.3 Sensitivity Analysis

A sensitivity analysis is crucial for assessing the robustness of variables. It demonstrates how variations in individual input factors impact the output, with all other factors held constant (Saltelli et al., 1999). The variables influencing the development of the residential building stock were not included in this analysis, as they were addressed in the development of three distinct socio-economic growth scenarios. These variables include population growth and the share of new construction activity.

5.4.3.1 Household types being constructed

The type of households being constructed plays a significant role into shaping cement demand, as each household type has a distinct level of cement intensity associated with its construction. This analysis examines how cement demand is influenced by different household types by assuming that only one type of household is constructed throughout the forecast period for each scenario. This assumption helps isolate the impact of household type on cement demand.

Figure 28 illustrates cement demand for Scenario High and Scenario Moderate, including both the demand projected in Sub-section 5.4.2, and the demand when only one type of household is being constructed throughout the forecast period. Scenario Low was not included in this figure to enable a clearer comparison. When only one-dwelling units are constructed, cement demand increases significantly. For Scenario High, cement demand more than doubled in 2050 compared to the initial assumptions, reaching 2374.7 ktonnes. In Scenario Moderate, demand increases by 646 ktonnes by the end of the forecast period, while in Scenario Low, it rises by 125.3 ktonnes. Conversely, when only two-or-more dwelling units are constructed, the scenarios show reduced cement demand compared to the initial assumptions. Specifically, cement demand reduces by 297.9 ktonnes in Scenario High, 430.7 ktonnes in Scenario Moderate, and 292.3 ktonnes in Scenario Low by the end of the forecast period.

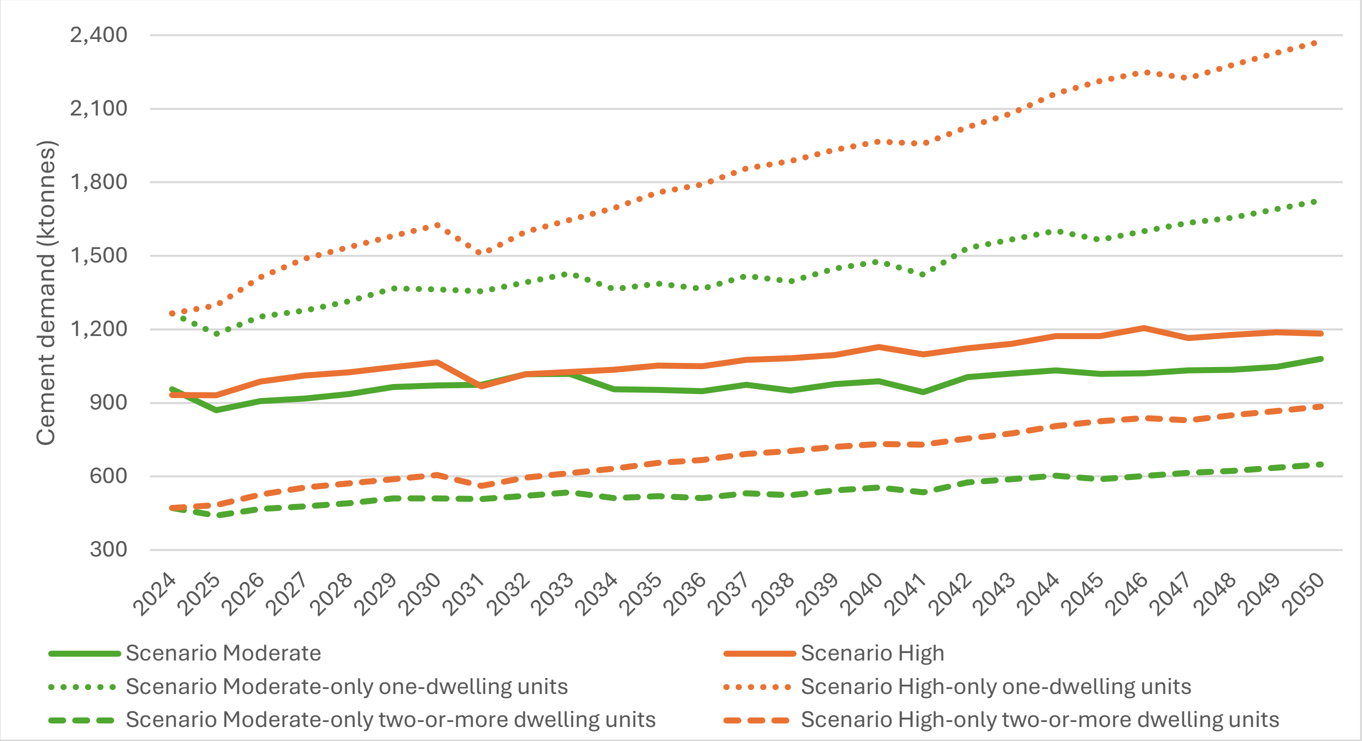

Figure 28: Cement demand in Scenario High and Scenario Moderate with different household types and initial assumptions.

5.4.3.2 Cement content in concrete structures

The cement content in concrete structures is a crucial variable influencing cement demand, as it directly affects the amount of cement required per unit of concrete produced. This analysis examines how changes in cement content affect cement demand over the forecast period, with all other factors held constant. The analysis explores a cement content of 7.5% throughout the forecast period compared to the initial assumptions, following Hoddinott, (2013) suggestion that cement content in concrete structures could be reduced up to 50% in 2050

Figure 29 illustrates the impact of maintaining a constant 7.5% cement content across all three scenarios. Reducing cement content led to a notable decrease in cement demand compared to the initial assumptions of all three scenarios. Specifically, by 2050, Scenario High shows a reduction of 353.8 ktonnes in cement demand, while Scenario Moderate and Scenario Low experience a decrease of 363.1 ktonnes and 216.1 ktonnes, respectively.

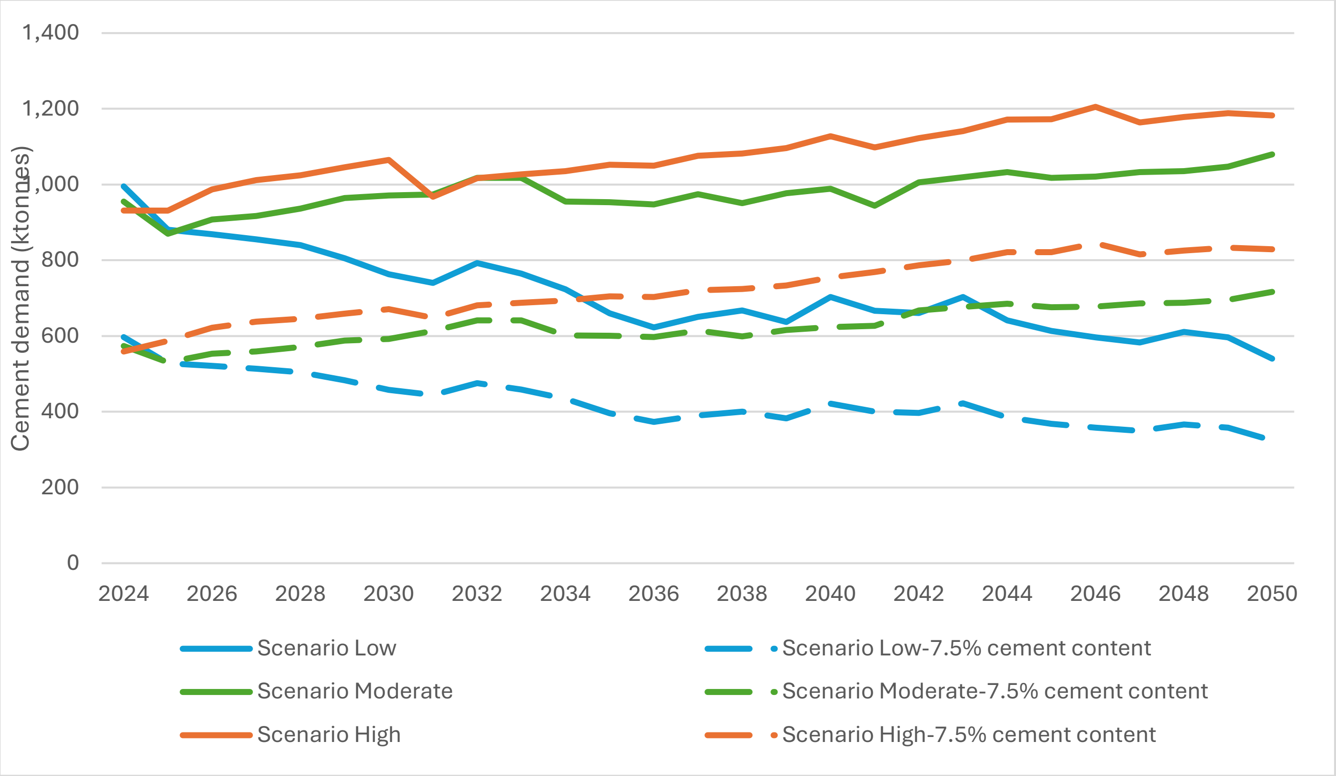

Figure 29: Impact of cement content on cement demand across all three scenarios.

5.4.3.3 Average floor areas

The average floor area of building types is another important variable that impacts the cement required for building construction. This analysis included a case where the possibility of reducing the average floor area by 10% was explored in accordance with the insights of GlobalABC, IEA and UNEP 2020 (2020), where the importance of reducing floor area growth is emphasized.

Figure 30 illustrates the impact of average floor areas on cement demand when a 10% decrease in average floor areas is applied across all three scenarios. Reducing the average floor areas of household types in the model results in lower cement demand compared to the initial assumptions, although not significantly. By 2050, cement demand reduced by 118.3 ktonnes in Scenario High, 120 ktonnes in Scenario Moderate, and 42.1 ktonnes in Scenario Low. These results highlight the influence of average floor area on cement demand and suggests that while decreasing floor area can contribute to lower cement consumption, its impact may be less significant compared to other variables like the household type and cement content.

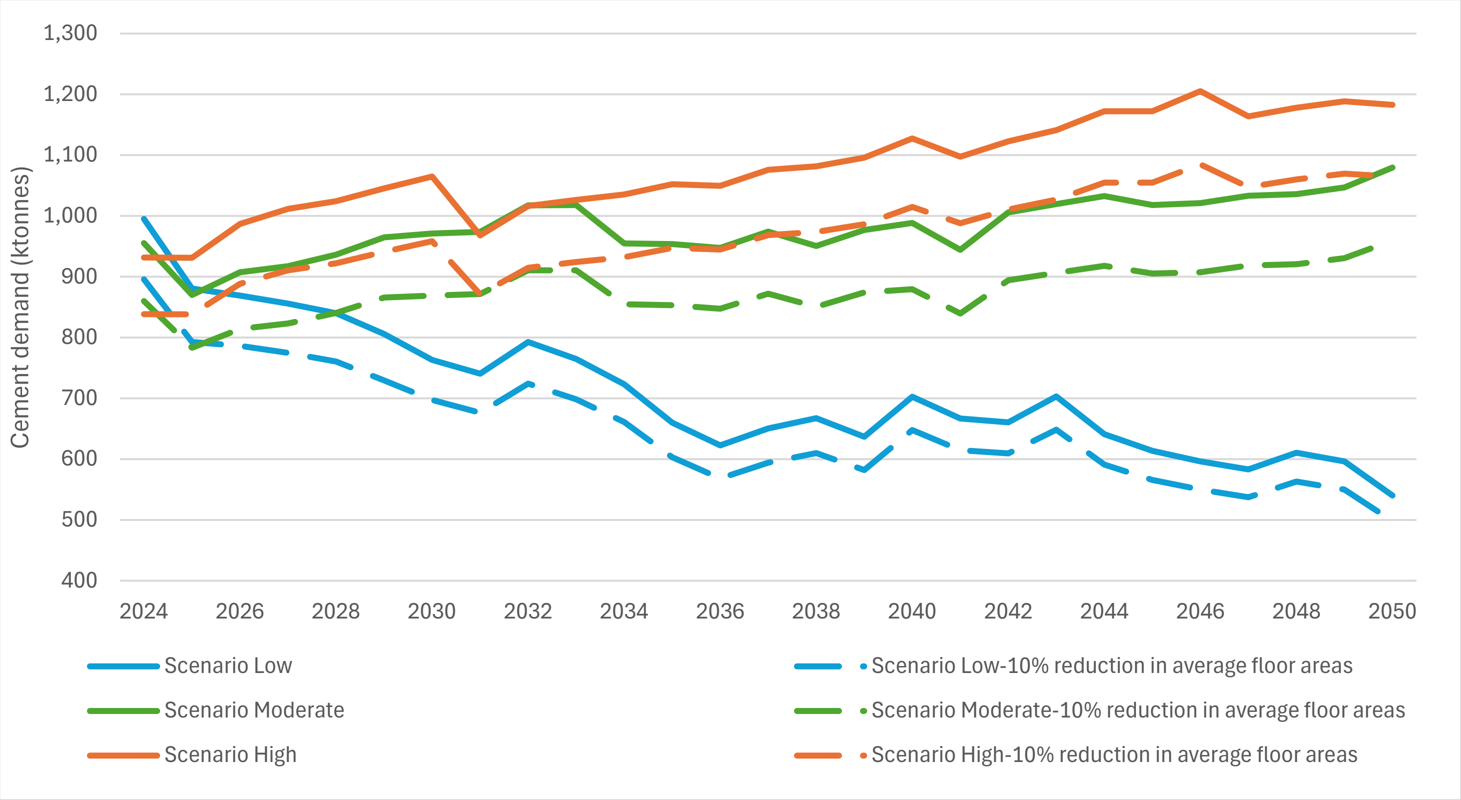

Figure 30: Impact of reduced average floor areas of household types on cement demand across all three scenarios.

5.5 Discussion and Conclusions

The validation of the cement demand model against historical data reveals both its strengths and limitations. The model effectively captures trends in cement demand related to the building sector and reflects overall patterns with reasonable accuracy, particularly when the building sector's influence on total demand is substantial. However, deviations such as the overestimation in 2007 and the underestimation in 2013 highlight the model's sensitivity to broader economic conditions and the significant impact of the civil engineering sector on overall cement consumption.

The varying projections of new residential floor surface areas and cement demand across the scenarios underscore the significant impact of socio-economic factors, specifically population growth, on cement construction. For example, Scenario Low, characterized by a high proportion of one-dwelling units and a decreasing population, initially exhibits the highest floor surface area but ultimately sees a decline in both floor surface area and cement demand over time due to decreasing population. Conversely, Scenario Moderate and Scenario High reflect increasing cement demand primarily driven by rising populations This reflects how demographic trends and housing preferences shape cement demand.

Sensitivity analysis further emphasizes the significance of key variables, with variations in household types, cement content, and average floor areas. The results of Sub-section 5.4.3.1 underscore the significant impact that the type of dwelling unit has on cement demand. The dramatic increase in cement demand when only one-dwelling units are constructed highlights the larger average floor area and associated cement intensity of these units, which drive up cement consumption. On the other hand, the decrease in cement demand when only two-or-more dwellings are constructed demonstrates the efficiency of these units in cement consumption. This contrast emphasizes the importance of dwelling type in shaping material demand and suggests that policy or planning decisions focusing on increasing the proportion of two-or-more dwelling units could lead to significant reductions in cement consumption within a region.

Furthermore, reductions in cement demand achieved by maintaining a lower cement content throughout the forecast period underscore the significant impact that variations in cement content can have on overall cement demand. This emphasizes the need to carefully consider cement content levels in cement demand forecasting models and make informed decisions regarding sustainable construction practices such as reducing cement content in concrete structures. While reducing average floor areas also contributes to lower cement demand, its effect is less pronounced, suggesting that while adjusting floor areas can be part of a strategy for managing cement demand, it should be complemented by more substantial measures such as optimizing cement content and increasing the proportion of two-or-more dwelling units.

In conclusion, while the model captures … of the residential sector, its application for the non-residential and civil engineering sectors was not possible due to limited easily accessible data for these sectors. Additionally, the model provides valuable insights into future cement demand attributed to the residential sector, however, its accuracy can be improved by accounting for evolving economic conditions, further technological advancements in the construction sector, and detailed construction practices. Continuous refinement and adaptation of the model are essential for reliable predictions and effective planning.

6 Discussion

6.1 Limitations and Theoretical Implications

The successful application of the theoretical framework developed in this study hinges on the availability and quality of data for end-users, socio-economic indicators, and cement intensity factors of the country under examination. For accurate results, the data must be granular and regional-specific to reflect the diverse construction activities and regulatory landscapes across the country under study. Forecasting socio-economic indicators and projecting structural changes are inherently complex and susceptible to unforeseen events, which can introduce uncertainty in the predictions. Additionally, it is important to acknowledge that while disaggregating end-user sectors offers a more nuanced approach, it can also increase data complexity and potentially introduce challenges in data collection and harmonization across different regions. Another significant limitation is the potential inaccuracies introduced by using average cement intensity factors. Different types of construction projects, even within the same category, can have widely varying cement requirements, while assuming an average floor area for building types might not accurately reflect variations in actual building sizes.

Furthermore, while the developed framework captures a significant portion of cement consumption, it does not account for the cement demand arising from other cement end-user sectors such as cement exports. However, applying this framework to all individual countries of the EU27 region could offer a comprehensive overview of the overall cement demand in the region, which could be then combined with a cement supply model that considers the details and dynamics of cement production and trading in the region to distribute demand.

Moreover, the model approach assumes that historical data on construction activities and cement usage can reliably predict future trends. However, this might not always hold true, especially in the face of unforeseen economic shifts, technological advancements, or changes in construction practices. These findings underscore the importance of incorporating economic factors and the full spectrum of construction activities into forecasting models to enhance their accuracy and reliability.

While existing models for forecasting cement demand generally incorporate socio-economic development assumptions, end-user sector activities, and cement intensity factors, the developed framework in this study differs in its level of detail regarding socio-economic development assumptions for specific regions and the level of disaggregation of end-user activities and sectors. Additionally, the developed framework allows for variations in cement intensity over time by considering structural changes within the construction and cement industry, an aspect which was often overlooked in existing models. These enhancements enable a more comprehensive modelling approach for forecasting cement demand, interconnecting specific socio-economic variables with the development of specific end-user activities and sub-sectors, structural changes, and cement intensity factors.

6.2 Future Considerations

Despite these limitations, the developed framework provides a valuable starting point for approximating cement demand in a specific region, although it provides a solid foundation for further development. Future research should focus on improving data granularity and accuracy, possibly through the integration of advanced data collection technologies such as remote sensing. Additionally, while the framework incorporates a wide range of influencing variables for forecasting cement demand, the modelled framework does not account for the entire spectrum of factors that could affect cement consumption. Refinements of the model could focus on incorporating details of the current and future building stock lifetime, including varying construction activities such as maintenance, demolition, and adaptive reuse, while also accounting for different vintage levels of construction activities and their impact on cement demand. Collaboration with industry stakeholders will be crucial for refining the model, addressing regional variations, and incorporating emerging trends and technological advancements, to ensure it remains a valuable tool for policymakers and industry leaders in understanding and planning for cement consumption.

7 Conclusion

The aim of this research was to develop a comprehensive framework for forecasting cement demand that integrates both bottom-up and top-down factors. The study began by investigating historical trends in indicators affecting cement consumption both across the EU27 region and at the country level, analysing their influence on demand. This chapter concluded that end-user indicators tend to demonstrate a stronger correlation with cement demand, highlighting the predictive power of the BPI for short-term cement demand projections for the building sector. Furthermore, it was highlighted that despite the weak correlation of socio-economic factors, fluctuations of socio-economic indicators heavily impacted the development of end-user indicators and consequently, cement supply and demand.

The next chapter reviewed current long-term energy models that include a cement sector module, complemented by insights from an expert interview to uncover key forecasting methods, practical considerations, and industry perspectives on cement demand modelling. While all models consider macroeconomic and demographic factors as drivers of cement demand, they vary in how these factors are translated into physical demand. Additionally, only one of the explored models included physical drivers of cement from end-user sectors, however, a clear explanation of how these end-user sectors develop in the forecast model was not provided. Overall, this chapter concluded that a more integrated approach that considers the physical demand of the end-user sectors, and structural changes is crucial for developing accurate and informative cement demand forecasts.

Furthermore, the next chapter focused on developing a conceptual framework for forecasting cement demand at the country level within the EU27, highlighting key influencing factors and their interconnections, while outlining a systematic approach for forecasting cement demand. The results of this highlighted a multifaced approach, demonstrating how the socio-economic environment in a region interacts with various end-user indicators, cement intensity factors, and structural changes to shape regional cement demand. While the framework developed offers a broad picture of cement demand forecasting, it also highlights the need for continual refinement to capture evolving trends and emerging factors in various sectors.

Finally, the framework was modelled, validated, and tested in a case study for the Netherlands, to assess the level of detail and accuracy of the framework in its practical application. The framework was specifically modelled for the residential building sector since its applicability to the non-residential and civil engineering sectors proved impractical due to the lack of publicly available data sources, specifically of average floor areas of non-residential buildings and construction GVA forecasts. When validated, the model demonstrated reasonable accuracy in capturing trends within the building sector, however, the model’s sensitivity to economic fluctuations and the impact of the civil engineering sector on overall cement consumption were highlighted as limitations.

Furthermore, the chapter explored different socio-economic scenarios and included a sensitivity analysis to assess the influence of various factors on cement demand projections. Cement demand for the residential building sector of the Netherlands ranged from 540 ktonnes to 1183 ktonnes in 2050 across the explored scenarios. The results revealed that population growth is the primary driver of cement demand in the model, while the sensitivity analysis demonstrated that changes in household types have significant effects on cement demand. The cement content in concrete structures also plays a crucial role, while variations in average floor areas contribute to a more modest impact on overall cement demand.

The primary research question aimed to determine which indicators should be included and how they can be utilized to model cement demand projections for a more accurate representation of the industry’s energy requirements in explorative decarbonization scenarios of the EU27 region. This research developed a comprehensive framework for forecasting cement demand by integrating both bottom-up and top-down factors, offering a nuanced view of how socio-economic factors influence various variables to shape cement consumption.

These findings underscore the crucial importance of strategically planning household types to manage cement demand effectively. Policymakers should prioritize the development of housing policies that encourage a higher proportion of two-or-more dwelling units over one-dwelling units. This shift is crucial as two-or-more dwelling units generally have lower cement intensity and contribute to more efficient use of materials. Additionally, given that cement content significantly impacts demand, investing in research and development to advance technologies that reduce cement content are crucial for managing cement consumption effectively. Finally, cement producers and policymakers should focus on gathering detailed, region-specific data on construction practices to enhance the accuracy of cement demand forecasts and support more effectively policy standards and material management. Such support could be achieved by incentivizing multi-unit developments, encouraging the use of advanced materials and technologies that reduce cement content while maintaining structural integrity, and ensuring that land-use and zoning policies are aligned with these goals.

References

Abalos, J. B., & Yeung, W.-J. J. (2023). Demographic, socioeconomic, and cultural factors for the rise in one-person households in developing countries: The case of the Philippines. *Journal of Population Research*, *40*(4), 20. https://doi.org/10.1007/s12546-023-09312-z

Adiguzel. (2024). *World Cement Industry Status, Trends & Outlook for 2024 Conquering the Global Market*. World Cement Association. https://worldcementassociation.org/images/download-selector/2024%20conference/Emir%20Adiguzel%20-%20Conquering%20the%20Global%20Market%20-%20Becoming%20a%20Global%20Leader.pdf

Ajumobi. (2020). *Cement and Types of Cement Used in Construction*. https://structville.com/2020/10/cement-and-types-of-cement-used-in-construction.html

Al Manaratain. (2019). *Choosing the Right Concrete: Ready-Mix vs. Precast*. https://almanaratain.com/choosing-the-right-concrete-ready-mix-precast/

Alaloul, W. S., Musarat, M. A., Rabbani, M. B., Altaf, M., Alzubi, K. M., & Al Salaheen, M. (2022). Assessment of Economic Sustainability in the Construction Sector: Evidence from Three Developed Countries (the USA, China, and the UK). *Sustainability*, *14*(10). https://doi.org/10.3390/su14106326

Almusaed, A., Yitmen, I., Myhren, J. A., & Almssad, A. (2024). Assessing the Impact of Recycled Building Materials on Environmental Sustainability and Energy Efficiency: A Comprehensive Framework for Reducing Greenhouse Gas Emissions. *Buildings*, *14*(6). https://doi.org/10.3390/buildings14061566

Ana Morgado & Paul Hugues. (2023). *Cement Industry*. https://www.iea.org/energy-system/industry/cement

Appolloni, L., & D'Alessandro, D. (2021). Housing Spaces in Nine European Countries: A Comparison of Dimensional Requirements. *International Journal of Environmental Research and Public Health*, *18*(8). https://doi.org/10.3390/ijerph18084278

Babalola, A., Musa, S., Akinlolu, M., & Haupt, T. (2021). A bibliometric review of advances in building information modeling (BIM) research. *Journal of Engineering Design and Technology*, *21*. https://doi.org/10.1108/JEDT-01-2021-0013

Bank of England. (2020). *How does the housing market affect the economy?* https://www.bankofengland.co.uk/explainers/how-does-the-housing-market-affect-the-economy

Barcelo, L., Kline, J., Walenta, G., & Gartner, E. (2014). Cement and carbon emissions. *Materials and Structures*, *47*(6), 1055–1065. https://doi.org/10.1617/s11527-013-0114-5

Beer, M., Kougioumtzoglou, I., & Patelli, E. (2014). *Maintenance and Safety of Aging Infrastructure* (pp. 121–162).

Bénétrix, A. S., & Lane, P. R. (2010). Fiscal Shocks and The Sectoral Composition of Output. *Open Economies Review*, *21*(3), 335–350. https://doi.org/10.1007/s11079-009-9161-5

Bouwberichten. (2024). *Woningbouwprojecten in Nederland*. https://bouwberichten.nl/bouwprojecten/woningbouw?gad_source=1&gclid=CjwKCAjw1emzBhB8EiwAHwZZxZmB4cT8CluT0HjGNauTaN0kjYpd3j4m01LgUgl3xKDhG0L-r_GOkxoCyswQAvD_BwE

CEMEX UK. (2021). *Mortar and Cementitious Products*. CEMEX UK. https://www.cemex.co.uk/documents/45807659/45840198/mortar-cementitious.pdf/46571b2a-3efd-4743-20c8-d33feb1aed9d

Chea, C. P., Bai, Y., Pan, X., Arashpour, M., & Xie, Y. (2020). An integrated review of automation and robotic technologies for structural prefabrication and construction. *Transportation Safety and Environment*, *2*(2), 81–96. https://doi.org/10.1093/tse/tdaa007

Cruz, G., Dizon, J. R. C., Farzadnia, N., Zhou, H., Margarito, M., Garcia, J. A., Liza, F. P., & Advincula, R. C. (2023). Performance, applications, and sustainability of 3D-printed cement and other geomaterials. *MRS Communications*, *13*(3), 385–399. https://doi.org/10.1557/s43579-023-00358-x

Dehghan, A., Maher, M. L. J., & Navarra, M. (2023). The Effects of Aggregate Properties on Concrete Mix Design and Behaviour. In S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. el Damatty, & G. Lovegrove (Eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* (pp. 457–468). Springer Nature Singapore.

Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, *42*, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Després, Keramidas, Schmitz, Kitous, Schade, Diaz Vazquez, Mima, Russ, & Wiesenthal. (2018). *POLES-JRC model documentation* (EUR 29454 EN). Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC113757

Doutres, S. (2022). *Mediterranean trading trends*. *International Cement Review*. https://www.cemnet.com/Articles/story/172051/mediterranean-trading-trends.html

Duchesne, J. (2021). Alternative supplementary cementitious materials for sustainable concrete structures: A review on characterization and properties. *Waste and Biomass Valorization*, *12*(3), 1219–1236. https://doi.org/10.1007/s12649-020-01068-4

Ede, A. (2014). Challenges Affecting the Development and Optimal Use of Tall Buildings in Nigeria. *The International Journal Of Engineering And Science (IJES)*, *3*.

Edelenbosch, O. Y., Kermeli, K., Crijns-Graus, W., Worrell, E., Bibas, R., Fais, B., Fujimori, S., Kyle, P., Sano, F., & van Vuuren, D. P. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, *122*, 701–710. https://doi.org/10.1016/j.energy.2017.01.017

EUROCONSTRUCT. (2023). *96th EUROCNSTRUCT Summary Report Winter 2023*. https://www.euroconstruct.org/ec_reports/summary-report/

European Cement Association. (2023a). *A low-carbon European concrete and cement sector in 2050*. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/#:~:text=Ordinary%20Portland%20cement%20can%20contain%20up%20to%2095%25,cement%20types%20in%20the%20EU27%20is%2073.7%25%201.

European Cement Association. (2023b). *Cembureau Activity Report 2022 Light*. https://cembureau.eu/media/m3jcyfre/cembureau-activity-report-2022-light.pdf

European Cement Association. (2024). *Cembureau: Clinker Substitution*. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/#:~:text=The%20use%20of%20other%20constituents,the%20EU27%20is%2073.7%25%201.c

European Commission. (2019). *Eurostat Statistics Explained. Glossary:Gross value added*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Gross_value_added&lang=en

European Commission. (2021). *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32010L0031

European Commission. (2022). *Building permits up by 15% in 2021*. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20221019-1

European Commission. (2023a). *Decarbonisation options for the cement industry*. https://publications.jrc.ec.europa.eu/repository/handle/JRC131246

European Commission. (2023b). *Eurostat Statistics Explained. Enlargement countries—Transport statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Enlargement_countries_-_transport_statistics#Road_network

European Commission. (2023c). *PRIMES Energy System Model*. https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-primes/

European Commission. (2024a). *Eurostat Statistics Explained: Building permit index overview*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Building_permit_index_overview

European Commission. (2024b). *Eurostat Statistics Explained. Construction production (volume) index overview*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Construction_production_(volume)_index_overview

European Commission. (2024c). *Population and population change statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_and_population_change_statistics#Population_change_at_national_level

European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, De Vita, A., Capros, P., Paroussos, L., Fragkiadakis, K., Karkatsoulis, P., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Gómez-Sanabria, A., Rafaj, P., Warnecke, L., Deppermann, A., Gusti, M., Frank, S., Lauri, P., … Kalokyris, T. (2021). *EU reference scenario 2020 – Energy, transport and GHG emissions – Trends to 2050*. Publications Office. https://doi.org/10.2833/35750

European Committee for Standardization. (2011). *EN 197-1:2011—Cement—Part 1: Composition, specifications and conformity criteria for common cements*. https://standards.iteh.ai/catalog/standards/cen/64d327b1-d5ac-45e3-8b04-fafec9e0698e/en-197-1-2011

Eurostat. (2024a). *Air transport infrastructure* [Dataset]. https://ec.europa.eu/eurostat/cache/metadata/en/avia_if_esms.htm

Eurostat. (2024b). *Building permits—Annual data* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/sts_cobp_a/default/table?lang=en&category=sts.sts_cons.sts_cons_per

Eurostat. (2024c). *EU trade since 2002 by CPA 2.1* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/ds-059268__custom_12584090/default/table?lang=en

Eurostat. (2024d). *GDP and main components (output, expenditure and income)* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/nama_10_gdp/default/table?lang=en

Eurostat. (2024e). *National accounts aggregates by industry (up to NACE A*64)* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/nama_10_a64/default/table?lang=en

Eurostat. (2024f). *Population on 1 January* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/tps00001/default/table?lang=en&category=t_demo.t_demo_pop

Eurostat. (2024g). *Production in construction* [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/teiis500/default/table?lang=en&category=t_sts.t_sts_cons

Eurostat. (2024h). *Railway transport infrastructure* [Dataset]. https://ec.europa.eu/eurostat/cache/metadata/en/rail_if_esms.htm

Eurostat. (2024i). *Road transport infrastructure* [Dataset]. https://ec.europa.eu/eurostat/cache/metadata/en/rail_if_esms.htm

Fleiter, T., Rehfeldt, M., Herbst, A., Elsland, R., Klingler, A.-L., Manz, P., & Eidelloth, S. (2018). A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. *Energy Strategy Reviews*, *22*, 237–254. https://doi.org/10.1016/j.esr.2018.09.005

Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). *Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente*.

Fridley, D., Zheng, N., Zhou, N., Ke, J., Hasanbeigi, A., Morrow, B., & Price, L. (2011). *China Energy and Emissions Paths to 2030* (LBNL-4866E, 1050675; p. LBNL-4866E, 1050675). https://doi.org/10.2172/1050675

GlobalABC, IEA and UNEP 2020. (2020). *GlobalABC Roadmap for Buildings and Construction 2020-2050*. IEA.

Harder. (2024). The Cement Industry in Europe at the Crossroads. *ONESTONE CONSULTING LTD*. https://www.zkg.de/en/artikel/the-cement-industry-in-europe-at-the-crossroads-4019235.html

Heincke, Maksimainen, Pacthod, Tai, Reiter, & Van Hoey. (2019). *Modular Construction: From Projects to Products*. McKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products

Heincke, Maksimainen, Pacthod, Tai, Reiter, & Van Hoey. (2022). *The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition*. MC Kinsey & Company. https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/the-circular-cement-value-chain-sustainable-and-profitable

Heincke, Maksimainen, Pacthod, Tai, Reiter, & Van Hoey. (2023). *Concrete and cement circularity could allow industry to rein in costs and reduce emissions, adding untapped value to the built environment.* MC Kinsey & Company. https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/the-circular-cement-value-chain-sustainable-and-profitable

Herbst, A. (2017). *Kopplung eines makroökonomischen Modells mit einem "bottom-up" Energienachfrage-Modell für die Industrie*. https://publica.fraunhofer.de/handle/publica/282087

Hoddinott. (2013). *Hoddinott, P. (2013). The role of CEMENT in the 2050 LOW CARBON ECONOMY Executive Summary.* https://lowcarboneconomy.cembureau.eu/wp-content/uploads/2018/09/cembureau-full-report.pdf

Howard, C., Dymond, C. C., Griess, V. C., Tolkien-Spurr, D., & van Kooten, G. C. (2021). Wood product carbon substitution benefits: A critical review of assumptions. *Carbon Balance and Management*, *16*(1), 9. https://doi.org/10.1186/s13021-021-00171-w

IEA. (2021). *Global cement demand for building construction, 2000-2020, and in the Net Zero Scenario, 2025-2030*. IEA, Paris. https://www.iea.org/data-and-statistics/charts/global-cement-demand-for-building-construction-2000-2020-and-in-the-net-zero-scenario-2025-2030, Licence: CC BY 4.0

IEA. (2023a). *Cement*. https://www.iea.org/reports/cement-3, Licence: CC BY 4.0

IEA. (2023b). *Global Energy and Climate Model*. IEA. https://www.iea.org/reports/global-energy-and-climate-model, Licence: CC BY 4.0

IEA. (2023c). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

Ige, O. E., Olanrewaju, O. A., Duffy, K. J., & Collins, O. C. (2022). Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method. *Energies*, *15*(7). https://doi.org/10.3390/en15072708

Ighalo, J. O., & Adeniyi, A. G. (2020). A perspective on environmental sustainability in the cement industry. *Waste Disposal & Sustainable Energy*, *2*(3), 161–164. https://doi.org/10.1007/s42768-020-00043-y

IRENA. (2020). *Business Models: Innovation Landscape*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Business_Models_Collection_2020.pdf

Kaur, G., Kaur, H., & Goyal, S. (2023). Correlation analysis between different parameters to predict cement logistics. *Innovations in Systems and Software Engineering*, *19*(1), 117–127. https://doi.org/10.1007/s11334-022-00505-y

Ke, Y., Zhang, J., & Philbin, S. P. (2023). Tradition and Innovation in Construction Project Management. *Buildings*, *13*(6). https://doi.org/10.3390/buildings13061537

Kermeli, K., Edelenbosch, O. Y., Crijns-Graus, W., van Ruijven, B. J., Mima, S., van Vuuren, D. P., & Worrell, E. (2019). The scope for better industry representation in long-term energy models: Modeling the cement industry. *Applied Energy*, *240*, 964–985. https://doi.org/10.1016/j.apenergy.2019.01.252

Kermeli, K., Worrell, E., & Crijns-Graus, W. (2016). Modeling the cement industry in integrated assessment models: Key factors for further improvement. *ECEEE Industrial Summer Study Proceedings*, *2016*, 207–221.

Kermeli, K., Worrell, E., & Masanet, E. (2011). *Energy Efficiency Improvement and Cost Saving Opportunities for the Concrete Industry*. https://doi.org/10.2172/937505

Koezjakov. (2017). *The Effect of an Increase in Energy Efficiency on Embodied Energy use A SCENARIO ANALYSIS FOR DUTCH RESIDENTIAL BUILDINGS*. https://studenttheses.uu.nl/handle/20.500.12932/25763

Koezjakov, A., Urge-Vorsatz, D., Crijns-Graus, W., & van den Broek, M. (2018). The relationship between operational energy demand and embodied energy in Dutch residential buildings. *Energy and Buildings*, *165*, 233–245. https://doi.org/10.1016/j.enbuild.2018.01.036

Krail, M., & Schade, W. (2014). *ASSIST Final Report-Summary of the Project Approach and Findings*.

Kristanto, J., Aryapratama, R., Ibrahim, M. A. A., Anasstasia, T. T., Azis, M. M., Kalza, A. L., Lestianingrum, E., & Hendranata, B. (2024). Assessing environmental impacts of utilizing recycled concrete waste from the technosphere: A case study of a cement industry in West Java, Indonesia. *Journal of Material Cycles and Waste Management*. https://doi.org/10.1007/s10163-024-02042-1

Lafhaj, Z., Rebai, S., AlBalkhy, W., Hamdi, O., Mossman, A., & Alves Da Costa, A. (2024). Complexity in Construction Projects: A Literature Review. *Buildings*, *14*(3). https://doi.org/10.3390/buildings14030680

Leese. (2021). *Concrete and cement: On the road to net zero*. https://ww3.rics.org/uk/en/journals/land-journal/concrete-and-cement--on-the-road-to-net-zero.html

Lehmann, S. (2019). Understanding the Benefits of Urban Density. In S. Lehmann (Ed.), *Urban Regeneration: A Manifesto for transforming UK Cities in the Age of Climate Change* (pp. 79–107). Springer International Publishing. https://doi.org/10.1007/978-3-030-04711-5_3

Li, N., Ma, D., & Chen, W. (2017). Quantifying the impacts of decarbonisation in China's cement sector: A perspective from an integrated assessment approach. *Clean, Efficient and Affordable Energy for a Sustainable Future*, *185*, 1840–1848. https://doi.org/10.1016/j.apenergy.2015.12.112

Li, Z., Bian, Y., Zhao, J., Wang, Y., Qiu, X., & Liu, Q. (2024). Sustainable building materials-recycled aggregate and concrete: A systematic review of properties, modification techniques, and environmental impacts. *Environmental Science and Pollution Research*, *31*(14), 20814–20852. https://doi.org/10.1007/s11356-024-32397-9

Loulou, Goldstein, Kanudia, Lettila, Remme, Wright, Giannakidis, & Noble. (2016). *Documentation for the TIMES Model*. IEA-ETSAP. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf

Lu, B., Li, M., Qian, S., Li, K. H. H., & Wong, T. N. (2024). High-Performance 3D Concrete Printing with Zeolite. In M. J. Tan, M. Li, Y. W. D. Tay, T. N. Wong, & P. Bartolo (Eds.), *Construction 3D Printing* (pp. 149–155). Springer Nature Switzerland.

Mathiesen, B. V., Johannsen, R. M., Kermeli, K., Crijns-Graus, W., Lund, H., & Skov, I. R. (2023). The green transition of industry – An introduction to IndustryPLAN. *Smart Energy*, *11*, 100111. https://doi.org/10.1016/j.segy.2023.100111

McNeil, K., & Kang, T. H.-K. (2013). Recycled Concrete Aggregates: A Review. *International Journal of Concrete Structures and Materials*, *7*(1), 61–69. https://doi.org/10.1007/s40069-013-0032-5

Meijer, F., & Visscher, H. (2008). Building regulations from an European perspective. *COBRA 2008. RICS Construction and Building Research Conference, 1-11. (2008)*.

Naqi, A., & Jang, J. G. (2019). Recent Progress in Green Cement Technology Utilizing Low-Carbon Emission Fuels and Raw Materials: A Review. *Sustainability*, *11*(2). https://doi.org/10.3390/su11020537

Neelis, M. L., & Patel, M. (2006). *Long-term production, energy use and CO2 emission scenarios for the worldwide iron and steel industry*.

Obrist, M. D., Kannan, R., Schmidt, T. J., & Kober, T. (2021). Decarbonization pathways of the Swiss cement industry towards net zero emissions. *Journal of Cleaner Production*, *288*, 125413. https://doi.org/10.1016/j.jclepro.2020.125413

Okae-Adow, M., Allotey, S., & Sasraku-Neequaye, B. (2015). *Comparative Cost Analysis between Asphalt Pavement and Concrete Pavement in Road Construction: A Case study using Concrete grade 35*. *7*, 94–104.

Oladiran, Hallam, & Elliott. (2023). *The Covid-19 pandemic and office space demand dynamics*. https://journals.vilniustech.lt/index.php/IJSPM/article/view/18003

Ortiz-Ospina & Roser. (2023). Government Spending. *Our World in Data*. https://ourworldindata.org/government-spending

Osareme, Muonde, Maduka, Olorunsogo, & Omotayo. (2024). *Demographic shifts and healthcare: A review of aging populations and systemic challenges*.

https://ijsra.net/content/demographic-shifts-and-healthcare-review-aging-populations-and-systemic-challenges

Paolo, C. (2007). *Sustainable recovery approach to the existing housing stock in Italy*.

PBL Netherlands Environmental Assessment Agency. (2021). *IMAGE- Integrated Model to Assess Global Enviroment-Documentation*. https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation

PBL Netherlands Environmental Assessment Agency. (2022). *Building permits number of dwellings and square meters* [Dataset]. https://www.cbs.nl/en-gb/custom/2022/36/building-permits-number-of-dwellings-and-square-meters

PBL Netherlands Environmental Assessment Agency. (2024a). *Dwellings and non-residential stock; changes, utility function, regions* [Dataset]. https://opendata.cbs.nl/statline/#/CBS/en/dataset/81955ENG/table?ts=1723715612266

PBL Netherlands Environmental Assessment Agency. (2024b). *Existing own homes; purchase prices, price index 2020=100, type of dwelling* [Dataset]. https://opendata.cbs.nl/statline/#/CBS/en/dataset/85791ENG/table?ts=1719484168150

PBL Netherlands Environmental Assessment Agency. (2024c). *Forecast: Nearly 18 million inhabitants, 19 million projected in 2037*.

PBL Netherlands Environmental Assessment Agency. (2024d). *Households; size, composition, position in the household, January 1* [Dataset]. https://opendata.cbs.nl/#/CBS/en/dataset/82905ENG/table

PBL Netherlands Environmental Assessment Agency. (2024e). *Population forecast* [Dataset]. https://www.cbs.nl/en-gb/our-services/methods/surveys/brief-survey-description/population-forecast

PBL Netherlands Environmental Assessment Agency. (2024f). *Population; Key figures* [Dataset]. https://opendata.cbs.nl/statline/#/CBS/en/dataset/85496ENG/table?ts=1719569377860

Research and Markets. (2024). *Netherlands Construction Industry Report 2023*. https://www.researchandmarkets.com/reports/5820961/the-netherlands-construction-market-size?utm_source=GNE&utm_medium=PressRelease&utm_code=k8r33j&utm_campaign=1928531+-+The+Netherlands+Construction+Industry+Report+2023%3a+Output+Projected+to+Grow+by+3%25+in+Real+Terms+-+Forecasts+to+2027&utm_exec=chdomspi

Richard Simon, Paul Hugues, Peter Levi, & Tiffany Vass. (2023). *Industry*. https://www.iea.org/energy-system/industry

Roorda, C., & Neelis, M. (2006). *Inclusion of production, energy use and value added for steel, cement and paper in the TIMER energy demand module*.

Saltelli, A., Tarantola, S., & Chan, K. P.-S. (1999). A Quantitative Model-Independent Method for Global Sensitivity Analysis of Model Output. *Technometrics*, *41*(1), 39–56. https://doi.org/10.1080/00401706.1999.10485594

Saviotti, P.-P., Pyka¤, A., & Jun, B. (2020). Diversification, structural change, and economic development. *Journal of Evolutionary Economics*, *30*(5), 1301–1335. https://doi.org/10.1007/s00191-020-00672-w

Sprecher, B., Verhagen, T. J., Sauer, M. L., Baars, M., Heintz, J., & Fishman, T. (2022). Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis. *Journal of Industrial Ecology*, *26*(1), 272–280. https://doi.org/10.1111/jiec.13143

Sprecher, B., Verhagen, T., Sauer, M., Baars, M., Heintz, J., & Fishman, T. (2021). Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis. *Journal of Industrial Ecology*, *26*. https://doi.org/10.1111/jiec.13143

Sverdrup, H. U., & Olafsdottir, A. H. (2023). Dynamical Modelling of the Global Cement Production and Supply System, Assessing Climate Impacts of Different Future Scenarios. *Water, Air, & Soil Pollution*, *234*(3), 191. https://doi.org/10.1007/s11270-023-06183-1

Szcześniak, A., Zychowicz, J., & Stolarski, A. (2020). Influence of Fly Ash Additive on the Properties of Concrete with Slag Cement. *Materials*, *13*, 3265. https://doi.org/10.3390/ma13153265

Tait, M. W., & Cheung, W. M. (2016). A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *The International Journal of Life Cycle Assessment*, *21*(6), 847–860. https://doi.org/10.1007/s11367-016-1045-5

Takva, Y., Takva, Ç., & İlerisoy, Z. Y. (2023). Sustainable Adaptive Reuse Strategy Evaluation for Cultural Heritage Buildings. *International Journal of Built Environment and Sustainability*, *10*, 25–37. https://doi.org/10.11113/ijbes.v10.n2.1060

Tan, C., Yu, X., & Guan, Y. (2022). A technology-driven pathway to net-zero carbon emissions for China’s cement industry. *Applied Energy*, *325*, 119804. https://doi.org/10.1016/j.apenergy.2022.119804

UNFCCC. (2023). *Greenhouse Gas Inventories—Annex I Parties* (United Nations Framework Convention on Climate Change) [Dataset]. https://unfccc.int/ghg-inventories-annex-i-parties/2023

Uratani, J. M., & Griffiths, S. (2023). A forward looking perspective on the cement and concrete industry: Implications of growth and development in the Global South. *Energy Research & Social Science*, *97*, 102972. https://doi.org/10.1016/j.erss.2023.102972

Vagtholm, R., Matteo, A., Vand, B., & Tupenaite, L. (2023). Evolution and Current State of Building Materials, Construction Methods, and Building Regulations in the U.K.: Implications for Sustainable Building Practices. *Buildings*, *13*(6). https://doi.org/10.3390/buildings13061480

Wei, J., Cen, K., & Geng, Y. (2019). China's cement demand and CO2 emissions toward 2030: From the perspective of socioeconomic, technology and population. *Environmental Science and Pollution Research*, *26*(7), 6409–6423. https://doi.org/10.1007/s11356-018-04081-2

Wilson. (2019). *The Potential of Prefab: How Modular Construction Can Be Green*. https://www.buildinggreen.com/feature/potential-prefab-how-modular-construction-can-be-green

Xavier & Oliveira. (2021). *Decarbonisation Options for the Dutch Cement Industry*. PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-cement-industry

Xu, C., Gong, Y., & Yan, G. (2023). Research on Cement Demand Forecast and Low Carbon Development Strategy in Shandong Province. *Atmosphere*, *14*(2). https://doi.org/10.3390/atmos14020267

Zamora-Castro, S. A., Salgado-Estrada, R., Sandoval-Herazo, L. C., Melendez-Armenta, R. A., Manzano-Huerta, E., Yelmi-Carrillo, E., & Herrera-May, A. L. (2021). Sustainable Development of Concrete through Aggregates and Innovative Materials: A Review. *Applied Sciences*, *11*(2). https://doi.org/10.3390/app11020629