Urban mining potential of non-residential buildings: Logistic centres as a case study in Santiago, Chile

Master Thesis – Master of Science in Industrial Ecology

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And lastly, to you, my beautiful angel.

Dedication

For my son, Domingo.

Every word carries the weight of your absence,
but none more than these.

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List of Abbreviations

BE	Built Environment
C&D	Construction and Demolition
CE	Circular Economy
EOL	End-of-Life
GIS	Geographic Information Systems
LC	Logistic Centre
MFA	Material Flow Analysis
MI	Material Intensity
MS	Material Stock
MSA	Material Stock Analysis
NRB	Non-Residential Building
SM	Supplementary Material
UM	Urban Mining

Executive Summary

Societal development has long depended on the intensive use of natural resources. Beyond fulfilling basic needs, materials provide a wide range of services that sustain and improve standards of living. However, resource extraction, transformation, and disposal result in significant environmental consequences. Within this context, the construction sector plays a central role, being the largest consumer of materials and the main source of solid waste.

Unlike many other material applications, buildings and infrastructure are designed to last and typically remain in use for decades. As a result, cities have accumulated vast amounts of materials over time that will eventually become available. This represents an opportunity to reduce the environmental pressures of the sector by recognising the built environment as a long-term material reservoir. However, using buildings as secondary resources requires, among other things, a comprehensive understanding of the material stocks they contain. Differences in building function and context define the magnitude and overall characteristics of the material stocks, resulting in heterogeneity across cities and underscoring the importance of adopting a cross-sectoral mapping approach.

Despite growing attention to material stock research, its development remains unevenly distributed. On the one hand, evidence from the countries of the Global South remains limited, particularly in regions such as Latin America, where severe constrains in data availability hinder resource management activities and the implementation of material recovery strategies. On the other hand, non-residential buildings are highly underrepresented in literature, despite containing large material stocks with distinct material profiles. Moreover, when the sector is studied, it is commonly grouped between broader categories, masking significant variations that are critical for urban mining strategies.

Against this background, this study focuses on the material stocks of logistics centres in Santiago, Chile, a rapidly expanding non-residential building sector that has almost doubled in the last 12 years, within a context where data availability is generally limited. However, comparatively good sector-specific data enables a detailed material stock assessment. This research aims to assess the urban mining potential of materials embedded in commercial logistics centres. Accordingly, the central research question guiding this study is: *What is the urban mining potential of logistics centres in Santiago?*

To answer the research questions, the study is structured in two stages. First, a spatially explicit material stock accounting is conducted, using georeferenced data combined with building-specific information, resulting in the quantification and characterisation of logistics centres. Second, a dynamic material flow analysis is applied, enabling the assessment of future material availability based on the previously quantified stocks.

Findings indicate that the sector contains over 5 million tonnes of material stocks with a highly homogeneous composition, with concrete accounting for more than 90% of total mass, while steel and masonry represent only minor shares. Materials are spatially concentrated, with a small number of municipalities and large logistics centres accounting for a disproportionate share of the total stock. Under the assumed building lifespans, most materials are expected to remain in use for several decades, with peak outflows projected around the 2070s. Despite a high degree of standardisation across the sector, material use varies substantially between companies, indicating the influence of construction choices on material consumption.

Despite the large magnitude of mapped material stocks, their urban mining potential is predominantly long-term. This temporal mismatch limits short-term recovery but provides an opportunity for anticipatory planning. In turn, the strong spatial concentration of stocks may facilitate large-scale recovery operations compared to dispersed actions across small-volume sites. However, the material composition of the stocks, particularly the dominance of concrete, raises doubts about the feasibility of material recovery under current conditions, as effective markets and incentives for its reuse or recycling remain limited.

This study contributes to the Industrial Ecology field and material stock research by providing the first spatially explicit material stock assessment in Chile, addressing both a geographical and a sectoral research gap. The methodological approach and datasets developed provide a transferable basis for extending the analysis to other contexts. In doing so, the study improves the understanding of how materials are distributed and used within logistics centres, supporting more informed discussions on material management and recovery strategies. More broadly, the findings reinforce the recognition of buildings as long-term material reservoirs and demonstrate that material stock assessments can generate valuable insights even in data-limited contexts.

***Keywords**: Urban mining, Non-residential buildings, Logistics centres, Material stock analysis (MSA), Material flow analysis (MFA), Circular economy, Geographic information systems (GIS).*

1 Introduction

Modern societies rely heavily on material and energy consumption to meet human needs. These resources are transformed into stocks such as buildings and infrastructure, which in turn, deliver essential services including housing, transport, and education (Haberl et al., 2021; Zuo & Zhao, 2014). Building and maintaining these systems requires vast material inputs, of which roughly 60% remain embedded (Krausmann et al., 2020).

As of 2018, the construction and operation of buildings accounted for over one-third of global final energy use and related CO_2 emissions (International Energy Agency [IEA], 2019). The sector is also the largest consumer of material resources and main generator of waste streams (IEA, 2019; Kamali et al., 2019). Moreover, material and energy flows are expected to increase with continued urbanisation, industrialisation, and limited uptake of secondary materials (Gao et al., 2023; Lanau et al., 2019). In this context, understanding the composition and dynamics of the built environment (BE) supports informed decision-making on material use, including the planning of their flows, waste management, and circular economy (CE) strategies (Cheng et al., 2018; Haberl et al., 2021; Kleemann et al., 2017; Mohammadiziazi & Bilec, 2022).

Against this background, recognising the BE as an anthropogenic reservoir highlights the importance of efficiently managing existing stocks and their future development (Bradshaw et al., 2020). Within this context, the CE aims to preserve material value, reduce extraction, close loops, and curb waste generation (Wuyts et al., 2022). In turn, Urban Mining (UM) builds upon these principles by explicitly targeting material recovery embedded within existing stocks (Ortlepp et al., 2016). To support these strategies, stock-based studies provide crucial information on the magnitude, composition and location of urban assets, which is essential for identifying future material sourcing alternatives as these stocks will eventually become available (Brunner, 2011).

In recent years, research on material stock (MS) has intensified, yet it remains strongly concentrated in the Global North, leaving developing countries comparatively understudied (Lanau et al., 2019). Research mainly focuses on residential buildings or specific materials, while non-residential buildings (NRBs) remain underexplored despite their importance as urban repositories (Ortlepp et al., 2016). This gap is especially relevant in emerging economies, where MS have not yet peaked but must still align with sustainable development goals (Krausmann et al., 2017, 2020). Latin America illustrates this uneven geographical coverage, as research on MS in the region has received comparatively little attention (Mesta et al., 2019). Chile further reflects this imbalance, with no urban-scale MS studies and material-level assessment applied mainly at national scale (Gallardo et al., 2014; Giljum, 2004; Muñoz & Hubacek, 2008; Steubing et al., 2010). This gap underscores the need for regional and sector-specific data about the MS potential. As Lanau et al. (2019) stresses, more spatially explicit case studies are needed, particularly in less studied geographical regions such as developing countries and NRB categories.

In this context, Chile's national commitment to a CE reinforces the need for reliable BE data, as such knowledge is critical for identifying MS with potential for circular use. Given the economic relevance of the construction sector and the scale of material consumption (Fundación Chile, 2020; León, 2022), identifying high-growth subsectors such as logistics offers a valuable entry point for stock-based studies. Logistics infrastructure has become increasingly strategic for national development, driven by economic growth, international trade, and port investment, aimed at improving connectivity and resilience to supply chain disruptions (Hurtado et al., 2022; Wilmsmeier & Sanchez, 2017). This strategic role is particularly relevant given the country's geography, its high exposure to climate change impacts (OECD, 2024), and recurrent exogenous shocks such as earthquakes.

Against this background, the logistics sector was selected as a case study to assess its UM potential, with a specific focus on their commercial logistics centres (LCs) in Santiago, Chile, the country's capital and main economic hub. This choice reflects their rapid expansion, spatial clustering, and relatively accessible data, critical for this type of studies. Their private ownership, defined boundaries, and simple, repetitive designs with limited material variation enhance the feasibility of quantifying and geolocating MS with greater precision compared to more complex building types.

1.1 Literature Review

Material stock and flows assessment in urban systems

Material Stock Analysis (MSA) and Material Flow Analysis (MFA) are widely used methods for quantifying and characterising MS and flows within urban systems. As operational efficiency in buildings improves, embodied impacts gain relevance within their life cycles, reinforcing the need to better understand existing MS and flows (Göswein et al., 2019). MFA are systematic assessments of stocks and flows within a defined system, which are bounded in both time and space, linking inputs, stocks, and outputs through mass balance principles (Brunner & Rechberger, 2004). Its purpose is to quantify the physical flows of materials and their accumulation within the economy and the environment, providing valuable information for management strategies (de Haes & Heijungs, 2009; van der Voet, 2002). In addition, combining MSA and MFA with Geographical Information Systems (GIS) enables spatial analyses of stock distribution (Bradshaw et al., 2020; Kleemann et al., 2017). From a use-phase perspective, MFA studies typically assess parameters such as building area, volume, material composition, age, and renovation frequency to estimate material replacement needs. In contrast, the end-of-life (EOL) perspective involves forecasting construction and demolition (C&D) waste volume and characteristics, to identify potential sources of secondary materials (Kleemann et al., 2017).

Over the past decade, interest in characterising anthropogenic stocks has grown, with studies addressing different scopes and purposes (Lanau et al., 2019). This interest has been driven by priorities such as CE principles, building disclosure policies, UM, and resource reuse strategies (Mohammadiziazi & Bilec, 2022). Many studies provide valuable insights into stock size, composition, and potential waste generation, but often lack spatial resolution and building-level detail, particularly when applied at aggregated or national scales. This limitation has been increasingly recognised in literature, with both Dai et al. (2025) and Streeck et al. (2025) emphasising the importance of improved spatio-temporal detail in existing research. For instance, Kral et al. (2014) analysed copper stocks in different cities across buildings, infrastructure, and devices to inform recovery strategies for recyclables and improve waste management practices. Similarly, Wiedenhofer et al. (2015) modelled mineral stocks in EU residential buildings and transport networks using national-level data to compare stocking and maintenance flows while forecasting EOL outputs. However, both approaches lack explicit spatial resolution, preventing the identification of MS locations and their surrounding context relevant for recovery.

Moreover, limited data availability and granularity at global scale further complicates the development of MSA and increases uncertainty in final stock estimates (Mohammadiziazi & Bilec, 2022).

Uneven global research focus

Building stock dynamics remain largely understudied in many regions, particularly in Africa, large parts of Asia, and Latin America, which have received significantly less attention compared to Europe, Japan, and China (Mohammadiziazi & Bilec, 2022; Streeck et al., 2025). This gap is especially concerning given the expected growth in these regions as they strive to achieve service levels comparable to those of developed countries (Gallardo et al., 2014). This lack of data significantly limits the ability to tap into additional secondary resources, particularly in these regions with frequent C&D (Mohammadiziazi & Bilec, 2022). However, such studies are highly dependent on data availability, which is limited in the Global South and often requires integrating multiple heterogeneous sources, as illustrated by Linares-Capurro et al. (2025), who assessed MS in relation to informality in Lima, Peru. A similar limitation is reported by Condeixa et al. (2017), who noted that even basic data on building materials are missing in Brazil, making it difficult to estimate how stocks change over time. Addressing this gap is crucial for unlocking material recovery and reuse opportunities in rapidly urbanising regions, where stakes are highest and data scarcest.

Non-Residential Building Stocks

Compared to the residential sector, available data on NRBs are often limited and aggregated, making detailed assessment challenging (Mao et al., 2020; Ortlepp et al., 2016). Studies show that NRBs tend to contain higher shares of metals and other valuable materials, as in the Rhine-Main area (Schebek et al., 2017). In Germany, they represent nearly half of national floor area and MS (Ortlepp et al., 2016), while in Beijing, they account for about 48% of total stocks, with concrete making up the dominant share of materials (Mao et al., 2020). Overlooking them risks underestimating their recovery potential, considering their specific material profiles and that they are demolished more often, which increase the availability of secondary materials (Mohammadiziazi & Bilec, 2022; Schebek et al., 2017). Within this context, Streeck et al. (2025) underscore the importance of advancing research on underrepresented building stocks, while Augiseau and Barl (2017) caution that grouping categories such as offices, logistics centres, or shopping malls hides significant variation, reinforcing the need for context-specific data. Together, these studies highlight both the potential and distinct characteristics of NRBs, while indicating limitations in the current research focus, emphasising the need for more disaggregated data.

Circular economy and urban mining potential

Research has increasingly examined the role of MS in supporting CE strategies, as urban stocks represent potential sources of secondary materials that can relieve pressure on primary resource extraction (Mohammadiziazi & Bilec, 2022). UM strategies seek to enable materials to re-enter existing cycles through targeted recovery actions (Brunner, 2011; Krook et al., 2011; Wallsten et al., 2015). In turn, Arora et al. (2020) define UM potential as the total MS within a city, where everything could be extracted for future use. As such, it is conceptualised as a theoretical upper bound, which in practice is progressively constrained by annual outflows, recovery efficiencies, material losses, and other practical complexities.

The literature has addressed the concept of UM from different perspectives. For instance, Cheng et al. (2018) quantified MS in Taipei, explicitly accounting for their spatial context to identify clusters with higher UM potential. In turn, Arora et al. (2021) examined the planning processes and feasibility conditions associated with building material recovery, whereas Tanikawa and Hashimoto's (2009) spatially explicit MSA created a database that serves as an input for potential supply of secondary materials in two different cities. Similarly, Hashimoto et al. (2009) estimated MS and future emergence of construction minerals in Japan, showing that about 30% of accumulated materials are likely to become waste or secondary resources, supporting future assessments.

According to Streeck et al. (2025), stock and flow assessments—such as those outlined above—do not directly ensure sustainable resource management; rather, they provide essential information for understanding BE dynamics, which in turn support the definition of optimal resource use strategies. However, in the Chilean context, despite the growing integration of CE principles into national and sectoral policy frameworks, including the National Roadmap to 2040 and complementary strategies targeting C&D waste (Construye2025, 2020; Martínez & Maluenda, 2021; Ministerio del Medio Ambiente, 2021), the material dimension of the BE and its potential as future urban mines remain weakly addressed.

1.2 Research gap

Despite advances in the understanding of MS dynamics in the BE, significant gaps persist in assessing the potential of embedded stocks. While recent studies have increased the level of detail of MS assessments, data availability remains limited and spatial resolution insufficient, particularly at building and component levels. In addition, NRBs are studied less extensively than the residential sector and are frequently analysed using aggregated categories, obscuring valuable differences in MS composition and dynamics. Moreover, large world regions are still underrepresented, particularly Latin America. Within this broader context, despite its recognised potential, stock-based research on the BE has not yet been developed in Chile, reflecting a data-scarce regional setting. This gap in the literature motivates this study, presenting an opportunity to expand knowledge in a context with limited empirical evidence.

1.3 Objective and research questions

Building on the research gap identified, the main objective of this study is to assess the urban mining potential of materials embedded in commercial logistics centres in Santiago, Chile. The results provide spatially explicit and building-level evidence on the sector's current characteristics, together with an anticipatory understanding of future material availability, contributing to more informed approaches to material use and management.

The overarching research question guiding this study is:

"What is the urban mining potential of logistics centres in Santiago?"

In this study, the assessment of urban mining potential is limited to existing material stocks embedded in logistics centres, considering their magnitude, material characteristics, spatial distribution, and temporal availability. The analysis refers to material stocks quantified up to the year 2024, which is defined as the reference year of the assessment.

The main research question is addressed through the following sub-research questions:

1. What is the total mass of materials in logistics centres?
2. What is the composition of materials accumulated?
3. Where are the material stocks located?
4. What will be the future dynamics of available materials?

1.4 Thesis Structure

The thesis is organised into five chapters, each addressing a specific phase of the research process:

- **Chapter 1: Introduction.** This chapter outlines the background and context of the study, presents the literature review, research gap, proposed objective and research questions.
- **Chapter 2: Methods.** This chapter describes the methodology and analytical steps adopted to address the research questions.
- **Chapter 3: Results.** This chapter presents a summary of the study's results.
- **Chapter 4: Discussion.** This chapter interprets the main findings and discusses their implications, including the study's validation, limitations, and recommendations.
- **Chapter 5: Conclusions**. This chapter summarises the main insights of the study, highlights its contribution, and outlines opportunities for future research.

2 Methods

This research aims to assess the UM potential of materials embedded in commercial LCs in Santiago, Chile. To achieve this, the study draws on the conceptual framework proposed by Arora et al. (2020) and their definition of UM potential to structure the analysis. They define UM potential as the total stock of materials and/or components accumulated within a city. In this sense, assessing the UM potential requires accounting for the quantity and composition of the stocks within a defined spatial context. Complementing this perspective, Graedel (2011) proposes three questions to be answered to assess the UM potential: *How many materials are there? What form do they take? And when they will be available?* These questions provide the basis for assessing UM potential and are consistent with the research questions guiding this study, supporting the selection of the methods used and structuring the analysis. ***Figure 1*** presents the analytical framework used in this study.

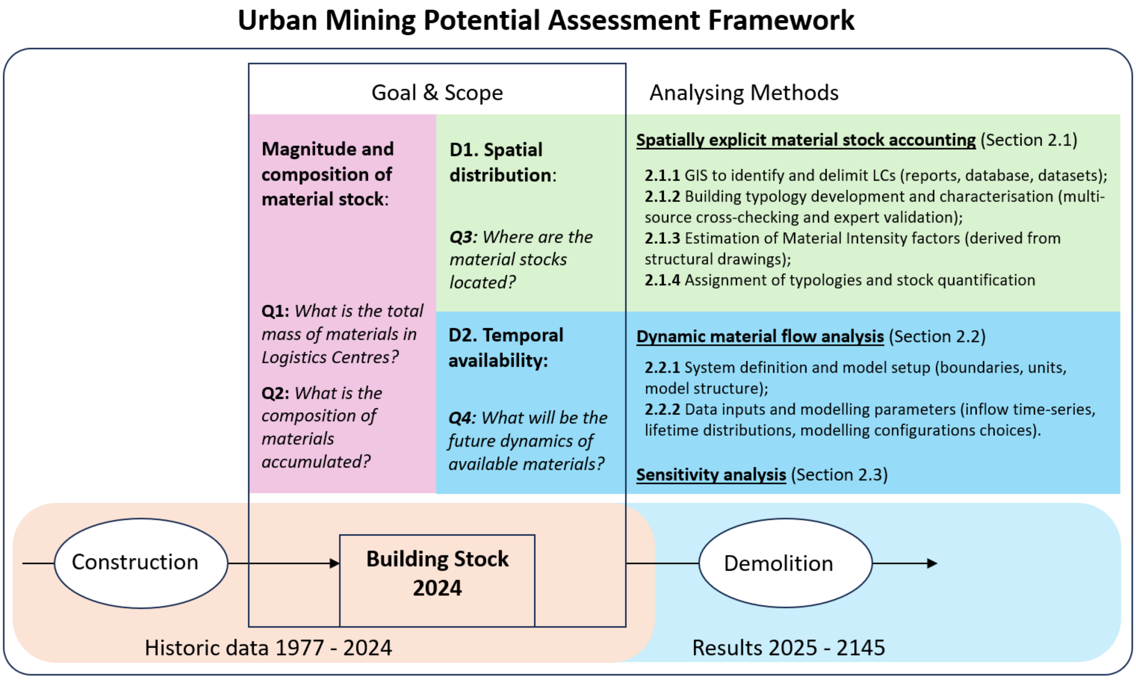

Figure 1. Methodological framework for the assessment of urban mining potential in commercial logistics centres.

The framework is structured around two analytical dimensions: a spatial dimension (D1) and a temporal dimension (D2), which use historical construction activity data to support the assessment of the UM potential. The scope of the analysis is limited to NRBs, specifically commercial LCs located in the Santiago Metropolitan Area, with stock accumulation reconstructed from the early development of the sector up to 2024. Within this framework, four sub-research questions (Q1–Q4) are addressed. Questions Q1 to Q3, related to the magnitude, composition, and spatial distribution of material stocks, are jointly addressed through a spatially explicit, bottom-up material stock accounting approach (**Section 2.1**). In this process, building locations, typological characterisation, and material intensity (MI) factors are progressively combined to translate spatial building data into quantified and geolocated MS. Question Q4, which focuses on the temporal availability of materials, is addressed through a dynamic material flow analysis (**Section 2.2**), using the quantified stock as input to estimate future material outflows under different lifetime configurations. Section numbers in the figure refer to the corresponding sections in this chapter, where each step is described in detail.

2.1 Material Stock Accounting

A bottom-up approach is adopted to develop the MS accounting, relying on the physical characteristics of the BE for the calculation. This approach enables the quantification of MS and the estimation of their composition with high spatial resolution. In practical terms, it involves obtaining georeferenced building footprints, defining representative typologies, classifying buildings, developing MI factors, and merging these data layers to derive MS estimates. This process is described in the following subsections, whereas a detailed data integration and processing workflow is presented in **Appendix A.1**.

2.1.1 Sector profiling and spatial delimitation of Logistic Centres

To characterise the logistics sector in Santiago, data were compiled from industry reports by real estate service firms (CBRE, Colliers, Cushman & Wakefield, and GPS) and from an in-house commercial report by Bodegas San Francisco (BSF), which also included information on the main companies in the market (***Table 1***). These sources provide aggregated and general information on location, total available floor area, surface area under construction, total warehouse floor area by submarket, and sectoral growth trends. This information supports the analysis of actors operating LCs in the region by providing an initial sector-wide characterisation of market size, spatial distribution, and main warehouse types. Among these actors, Bodegas San Francisco played a central role, granting access to their facilities and proprietary information on construction characteristics, economic aspects, and broader sector practices. This input was important for this research as it supported the initial profiling and spatial scoping of the logistics sector.

Table 1. Main data sources for Step S1.1: Profiling logistics actors and LC localisation

Source name	Type	Website	Reference
CBRE	Real estate service firm	www.cbre.cl	(CBRE, 2025)
Colliers	Real estate service firm	www.colliers.com/es-cl	(Colliers, 2025)
Cushman & Wakefield	Real estate service firm	www.cushmanwakefield.com/es-cl/chile	(Cushman & Wakefield, 2025)
GPS	Real estate service firm	www.gpsproperty.cl	(GPS, 2025)
BSF	LC developer & operator	www.bsf.cl	(SM 1.1)

Starting from the centre-level database provided by Bodegas San Francisco, the analysis was first restricted to the Metropolitan Region and subsequently ordered by the total constructed area of each LC. This dataset provided an initial approximation of the size of the logistics sector. To focus on the most significant share, only LCs with a built surface greater than 30,000 m^2 were retained, collectively representing about 80% of the total constructed surface. This threshold served as a preliminary filter to prioritise centres by narrowing the number under study. Increasing the coverage to 85% or 90% would have required expanding the sample size by approximately 20% and 43% more centres, respectively, which was considered too resource-intensive and time-consuming for the scope of this thesis. In subsequent steps, the number and size of each LC and its individual buildings were validated in greater detail, and additional actors could be incorporated where relevant. At this stage, only three records were excluded from the analysis: one corresponded to a privately owned facility not available for rental, another to a similar case operated internally by a logistics company, and the third was a duplicate entry in the original database.

This selection process resulted in a working set of LCs representative of the Metropolitan Region. This dataset formed the basis for the following stages, beginning with the creation of georeferenced LC polygons and subsequent data harmonisation and processing. All data compiled in this step were harmonised to represent the situation of LCs in 2024, which was defined as the reference year of the analysis.

Spatial Delimitation of Logistic Centres

The spatial representation of LCs was carried out in QGIS, an open-source software that allows users to view, edit and analyse geographic data. The official national projection for Chile (EPSG:5361 – SIRGAS-Chile 2010 / UTM zone 19S) was used to ensure appropriate accuracy for distance and area calculations. Using previously collected information, together with .kmz files, company websites, and Google Maps locations, each centre was manually digitised on the software's map and converted into georeferenced layers. Each layer consists of polygons with clearly defined boundaries that represent the exact extent of each facility. A coding system was developed to organise the dataset, combining company identifiers, LCs names, and additional relevant attributes linked to each polygon. Complementary information was consulted from the Chilean Environmental Impact Assessment System (SEIA), which requires industrial projects located on plots larger than 20 hectares to be submitted for environmental assessment (Ministerio del Medio Ambiente, 2012; Sistema de Evaluación de Impacto Ambiental, n.d.). Where records were available, SEIA data were used to cross-check the location and extent of LCs, although coverage for older centres was limited. Once polygons were completed, the total area of each LC was calculated in m^2 and integrated into the polygon attribute table. This layer represented the first dataset to be employed in the subsequent step of data processing, serving as the main input for harmonisation and further analysis.

Data Harmonisation and Processing

The harmonisation process began with the download of the national building footprint dataset from Geofabrik (OSM) (Geofabrik, n.d.) and the official records of the municipalities' boundaries (Ministerio de Bienes Nacionales, n.d.). As the OSM dataset contained polygons for the entire country, the first step was to clip it to the LC polygons developed in the previous section, restricting the analysis to the Metropolitan Region. The subset was then reviewed to identify inconsistencies, with missing warehouses added and existing shapes corrected. Adjustments were made using satellite and 3D imagery, guided by roof structures, road markings, and other visible features, specifically for irregular geometries and overall consistency. OSM building shapes served as a base, but were modified wherever discrepancies were found, giving priority to the most recent high-resolution sources.

The process resulted in two geospatial layers: one with the LC polygons and another with all warehouse footprints. Although both layers could be merged to calculate building areas and aggregated LC surfaces, keeping them separate was preferred to maintain flexibility for subsequent analysis. Each layer incorporated company and centre codes, and a detailed record of processing steps was maintained in a file processing logbook, available in the

Supplementary Materials (SM) section (SM 1.3, 3.1, 3.2), which also presents the repository structure and access link.

2.1.2 Development of Building Typologies

For the development of the typologies, publicly available information from the Chilean Revenue Service (SII) was first analysed (Servicio de Impuestos Internos [SII], n.d.-b). This step aimed to assess whether construction typologies could be defined directly from official cadastral records. The Service provides cadastral records linked to property IDs, which were first examined to determine their scope and identify additional details required for this task. In addition, the SII web-based map was consulted to retrieve the property ID of each specific LC (SII, n.d.-a), with each location verified against the QGIS layer created earlier. At this stage, a manual, case-by-case review was carried out to obtain each property ID. As the SII dataset covers the entire country, the records were processed and structured using a dedicated script (code available in SM 1.4 and 1.5). However, the information available in these records was limited and often poorly structured; nevertheless, it includes basic attributes such as declared use, total area, and, in some cases, the year of construction, the latter being particularly useful for the dynamic MFA. As such, SII data were retained to support property identification and to retrieve construction years when unavailable from other sources, based on the “Year of construction line” field (column V7), but not used to define construction typologies.

The previous step did not provide sufficient detail to characterise construction systems or define representative typologies. Therefore, an overview document was created for each LC using satellite imagery from QGIS, Google Maps, Street View, and other publicly available photographs to understand the types and variety of buildings present. The documents are provided in the SM (1.6 and 1.7). This visual documentation was complemented with a review of publicly available industry information from company websites and other online sources to identify key design and construction characteristics, particularly structural systems and clear height. For each project, declared eave and ridge heights were recorded when available, together with any additional technical information explicitly reported. This included information on structural systems and complemented by qualitative observations from visual inspection to identify common characteristics between LCs. The resulting compilation is presented in **Appendix A.2** (***Table A. 2***), with the corresponding list of sources provided in ***Table A. 1***.

In the case of Bodegas San Francisco warehouses, primary data were provided, allowing the direct derivation of high-accuracy typologies for all buildings in the sector sharing similar construction characteristics. While the previous steps were applied consistently across all companies as part of the sector-wide data compilation, typology definition for Bodegas San Francisco relied on primary building-level information and was subsequently extended to other companies exhibiting comparable construction systems. As this company alone represents roughly one third of the sector, these typologies offer a strong empirical basis for the overall classification. For the remaining companies, publicly available information was often limited. Therefore, the compiled material was reviewed together with the engineering department at Bodegas San Francisco, which helped to establish the main structural systems present across the industry. As shown in ***Table A. 2***, a wide range of construction methods are used, with steel, masonry, and concrete as the predominant materials. Reported clear heights typically range from 6.5 metres for confined masonry warehouses to up to 12 metres in concrete structures. Based on this assessment, representative building typologies were defined to capture the most recurrent structural materials, height ranges and external finishes observed. Where architectural drawings or primary design documentation were available, as in the case of masonry-built warehouses, typologies were directly derived from the actual construction systems employed. In contrast, where information was limited and originated from multiple projects with only partial public data, typologies were defined by identifying the main construction systems and assigning a limited set of representative and comparable heights within the observed range. The defined typologies refer to standard open-space warehouse, as typically delivered to tenants upon rental. Subsequent modifications or additions, which vary widely across businesses, fall outside the scope of this research.

Following standard practice in MSA studies, typologies were treated as archetypes representing groups of buildings with similar material characteristics. Specific MI factors were then assigned according to their construction systems and material configurations. To maintain consistency with established terminology and avoid introducing barriers to reproducibility in MSA research, as highlighted by Mohammadiziazi and Bilec (2022), this study focuses on NRBs, specifically the functional subcategory “warehouse”.

2.1.3 Development of Material Intensity

The previous step defined representative buildings for the sector, providing the initial input for linking physical characteristics with material usage. In this section, MI factors are derived from these archetypes and other relevant sources.

To develop the coefficients, external technical advice from structural engineers was used to translate construction blueprints into representative MI factors for each building typology, ensuring a consistent interpretation of structural systems and material quantities. For masonry warehouses and self-storage units, original blueprints from the sector were reviewed, while for steel and concrete structures, warehouse designs from related industries were adapted to fit the sector’s observed characteristics. In all cases, layouts and heights were adjusted to align with the defined typologies.

The process involved first ensuring that the available blueprints matched the representative typologies in terms of dimensions, layouts, and clear heights. Subsequently, each structural and architectural element, such as beams, slabs, roof structures, walls, trusses, panels, and other components, was quantified and translated into mass per unit area. All typologies, except self-storage units, were complemented with internal structures to account for the materials associated with office areas, which are common in warehouses but often missing from official plans, as these spaces are typically incorporated at later stages of the project and are not included in original structural drawings. The detailed reasoning and intermediate calculations used to derive these coefficients are provided in the SM (1.8), together with reference images of the blueprints used in the process.

Consistent with standard practice in MSA studies, the MI factors developed are expressed in kilograms per square metre (kg/m^2). As highlighted by Mohammadiziazi & Bilec (2022), MI is a key parameter in MSA, and more precise determination of archetypes increases the accuracy of results while mitigating uncertainty. Thus, given the quality of the data available for this study, MI factors were disaggregated to the component level (columns, beams, walls, floors, and roof elements), rather than aggregated at the material level. Although not represented in three dimensions, this disaggregation enables a more precise attribution of materials to specific building elements in the GIS attribute table, thereby improving the accuracy of the mapped stocks. The following section explains how these MI factors were used to calculate MS.

2.1.4 Material Stock Calculation

The first step in calculating the MS is to assign each warehouse to one of the developed typologies. Each typology is characterised by distinct physical attributes, which allow consistent classification. In this case, classification is based primarily on the structural material of walls and columns and, secondly, on warehouse height. When the building type could not be clearly identified from available documentation, the following procedure was applied. First, Street View imagery or on-site inspection was used to identify the main characteristics. If this was not conclusive and the company operated other buildings already classified, the same typology was assigned assuming standardised construction practices. Otherwise, buildings were classified by comparison with similar warehouses operated by other companies. In practice, all buildings could be classified using this approach.

With buildings assigned to each typology in QGIS, the MS are calculated using the typology-specific MI factors. These coefficients can be defined at the component level (e.g., steel in walls, steel in roofs, concrete in floors, concrete in columns) or at the material level (e.g., steel, concrete, brick).

Component-level calculation (Eq. 1):

$$MS_{(b,c)} = TGFA_b \times MI_{(t,c)} \tag{1}$$

- $MS_{(b,c)}$: stock of component c in building b.
- $TGFA_b$: total gross floor area of building b.
- $MI_{(t,c)}$: material intensity of component c for typology t.

Material-level calculation (Eq. 2):

$$MS_{(b,m)} = TGFA_b \times MI_{(t,m)} \tag{2}$$

- $MS_{(b,m)}$: stock of material m in building b.
- $MI_{(t,m)}$: material intensity of material m for typology t.

The total MS of a building (MS_{total}) can be obtained as the sum of all materials (Eq. 3). This is equivalent to summing the stock of all components (Eq. 4). Both lead to the same value; the difference lies in the chosen level of disaggregation.

$$\sum_m MS_{(b,m)} = MS_{Steel} + MS_{Concrete} + MS_{Brick} + MS_{Mortar} + MS_{Others} \tag{3}$$

$$MS_{total} = \sum_m MS_{(b,m)} = \sum_c MS_{(b,c)} \tag{4}$$

The calculation was performed in QGIS by multiplying each building's footprint by its corresponding MI factor. The resulting attribute table was then exported for further analysis and calculations in a spreadsheet provided in the SM (1.10).

2.2 Dynamic Material Flow Analysis

To conduct the second analysis, a dynamic MFA model was applied to estimate future material outflows from the current stock, allowing to estimate when MS may reach their EOL.

There are several ways of classifying MFA depending on the focus and structure of the analysis. For instance, how flows are defines, what drives system changes, how outflows are estimated, or how MS are derived. A concise summary of the most common methodological distinctions used in MFA studies is provided in **Appendix B.1**. In turn, the next section presents the specific methodological choices, assumptions, and procedures applied in this research to develop the dynamic MFA model. A detailed data integration and processing workflow is presented in **Appendix B.2**.

2.2.1 System definition

The quantification of MS was carried out in the previous step, so the spatial boundaries of the system remain the same. All material flows described in the model are therefore limited to this defined area. Administratively, the boundary corresponds to the Metropolitan Region, specifically the provinces of Santiago, Chacabuco, and Maipo. Functionally, the study focuses only on the commercial LC identified in the previous analysis.

The time unit considered is one year, and all flows are expressed in tonnes per year for the calculations. For presentation purposes, results may be aggregated (e.g. million tonnes), though it will be explicitly stated in the units. The temporal scope of the analysis extends from the earliest known stock, using the construction year of the buildings identified and documented in the previous section, to the last expected outflow.

The MFA model is designed to analyse materials over time at the component level. This makes it possible to track each component from its entry into the system until it leaves it. Materials are grouped according to four main components, Roofs, Walls & Columns, Floors, and Others, and further classified into sub-categories such as steel structures, metal panels, bricks, concrete, among others.

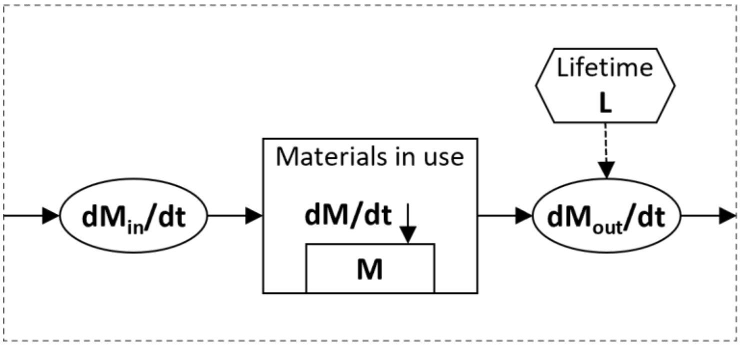

Figure 2. Conceptual outline of the flow dynamic model. Dashed lines represent influence, while solid lines denote direct material flows. *M* indicates material stocks, *dM/dt* the net stock accumulation of materials, *dM_{in}/dt* the input flow, and *M_{out}/dt* the output flow. *L* represents the warehouse lifetime determinant.

In ***Figure 2*** the conceptual model developed in this research is presented, applied to the materials used in the logistics sector. In the figure, processes are represented by rectangles, ovals represent the flows, while external determinants, are depicted as hexagons. Other dynamic MFA models work with external parameters to obtain the total gross floor area, its yearly inflow, and material use. However, because the yearly material inflow has already been calculated in the previous analysis, a simplified model is used to estimate the future destocking flows.

The model follows a flow-driven approach, where the system's evolution is determined by materials inflows rather than by predefined stock target. This approach does not aim to determine future resource demand, but to analyse how materials leave the existing stock over time. Using the delay model approach to estimate material lifespan, the outflows are determined as a function of the historical inflows and the lifetime distribution. This aligns with Müller (2006), who considers that the input-lifetime approach leads to reliable results for long-lived materials whose inflows are already known and measured. Since the purpose of the study is to understand the UM potential of current stocks rather than to forecast future resource demand, future inflows or socio-economic variables that could alter the system are not considered. The analysis is therefore exploratory in nature, focusing exclusively on the destocking process of existing building.

As with most MFA studies, some simplifications were made. In this case, the model does not account for continuous flows associated with operational maintenance activities (e.g. repairs, replacements, and upkeep), as these are implicitly assumed to preserve the existing stock rather than modify it over time. This assumption aligns with the aim of the study, which focuses on assessing material stock from an EOL perspective. However, this does not imply that maintenance-related flows are not significant, but rather that they fall outside the scope of the system analysed here.

The model works with inflow, outflow, and stock rates. The inflow (dM_{in}/dt) represents the yearly amount of materials entering use, while the outflow (dM_{out}/dt) corresponds to the quantity leaving the stock as demolition occurs. The net rate of change in the material stock is expressed as dM/dt. In this sense, it can be described as a balance between the inflow and outflow, as shown in Equation (5).

$$\frac{dM(t)}{dt} = \frac{dM_{in}(t)}{dt} - \frac{dM_{out}(t)}{dt} \tag{5}$$

Outflows are calculated as the combination of the inflow time series and the lifetime probability density function $L(t, t')$, which gives the probability that materials entering use in year t' reach their EOL at year t, as shown in Equation (6). Although it is written in continuous form, the model uses yearly data, where inflows and outflows are calculated discretely for each year.

$$\frac{dM_{out}(t)}{dt} = \int_{t_0}^{t'} L(t, t') \cdot \frac{dM_{in}(t')}{dt'} dt' \tag{6}$$

In MFA studies, different distributions are commonly used; however, due to the lack of empirical data and for simplicity, a normal distribution was adopted here, following Hu et al. (2010) and Müller (2006). The corresponding lifetime probability density function is defined by the mean lifetime (τ) and standard deviation (σ):

$$L(t, t') = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau)^2}{2\sigma^2}} \tag{7}$$

2.2.2 Data inputs and modelling parameters

The implementation of the model uses inflow data over time and assumptions on material lifespans. This section describes the used datasets and parameters to estimate future material outflows from the current stock, as well as the main assumptions applied in the modelling process.

Inflow time-series

The inflow data used in this model were taken from the previous analysis. They represent the amount of materials added to the building stock each year, in tonnes per year. As the total stock was already derived from yearly inflows, these values can be used directly after grouping them by year. Each year therefore includes only the new materials entering the system, while the inflows are kept separated by component to track the composition of each cohort. Combining these inflows with the lifetime distribution allows estimating when materials in use will reach their EOL and leave the stock.

Construction year data used to build the inflow time-series were obtained following a simple order. First, primary information was used for BSF centres (around 190 buildings). Then, historical images from Google Earth were checked to identify the approximate construction year. After that, cadastral records from the SII were reviewed, and when no record was found, the year was estimated using context information from neighbouring buildings or the surrounding area. This affected less than 5% of the total dataset.

Lifetime distribution

Given the limited availability of empirical data on building service life and demolition activity in Chile, and the absence of consistent official records at the sectoral scale, simplified lifetime assumptions were required for the dynamic MFA.

Accordingly, an average lifetime of 60 years was adopted, consistent with previous stock and flow studies in Chile (Gallardo et al., 2014). Although this value was originally estimated for the residential sector, it was extended here to NRBs due to the lack of specific data for this category. In contrast to Gallardo et al. (2014), where this value was used to obtain a fixed demolition rate, it is applied here as the mean lifetime (τ) of the lifetime distribution presented in Equation (7). This assumption is consistent with the 40-80 year range provided by the Chilean National Revenue Service for solid constructions, including steel, reinforced concrete, and masonry structures (SII, n.d.). According to correspondence with Bodegas San Francisco (J. Barros, personal communication, 2025), typical payback periods in the sector range between 10 and 15 years. This means that the chosen lifespan lies well above the minimum operational expectation, offering a reasonable lower bound for the modelling choices discussed below. For simplicity and following Hu (2010), the standard deviation was set as 20% of the mean value.

The adopted normal lifetime distribution was first truncated to the range 30–120 years to avoid unrealistically short or long lifetimes and subsequently normalised. Additionally, to ensure that buildings still in use in 2024 remain in the stock at the start of the analysis, the distribution was further truncated and re-normalised so that outflows begin only after 2025. For the adopted parameters, the probability mass that would be excluded by truncation if not renormalised is limited to approximately 0.6% below 30 years and is negligible above 120 years, indicating a minimal effect of truncation on the results.

Further discussion on alternative lifetime estimation approaches and data limitations in the Chilean context is provided in **Appendix B.1**.

Modelling configurations

Given the exploratory nature of the prospective analysis, three complementary modelling configurations were defined to estimate and represent future material outflows from current stock. The configurations do not represent alternative future scenarios, but rather different ways of structuring the same system to address distinct modelling objectives. All configurations start from the same stock baseline in 2025 but differ in how lifetimes and construction inflows are represented and aggregated. Together, they support the interpretation of spatial patterns, temporal dynamics, and aggregation effects in future material availability.

1. **Configuration 0 – Deterministic lifetime:** applies a fixed lifetime of 60 years to each warehouse. The objective of this configuration is to preserve spatial resolution and to support the identification of where MS are ageing across the study area. It is mainly used to locate materials approaching their EOL and the areas where initial releases may occur, rather than to simulate continuous outflows over time.
2. **Configuration 1 – Probabilistic per warehouse**: applies a normal lifetime distribution to each warehouse individually, using disaggregated construction years as inflows. The objective of this configuration is to represent the temporal dynamics of material release at the building level, introducing lifetime dispersion while retaining warehouse-level resolution. This configuration is used as the main representation to estimate when materials embedded in warehouses may become available over time. Shared external paved areas are excluded, as their representation would require subdividing each centre into multiple external pavement polygons with reliable construction year data, which is not available.
3. **Configuration 2 – Probabilistic per centre:** applies the same normal lifetime distribution as Configuration 1 but aggregates construction inflows at the LC level by assigning a single representative construction year per centre, calculated as the built area weighted average of the construction years of its warehouses. The objective of this configuration is to examine how inflow aggregation choices affect the resulting outflow dynamics, while retaining annual, material- and component-level resolution in the outputs. This configuration provides a complementary representation of the same system based on a more aggregated inflow structure and enables the inclusion of shared external paved areas.

The calculations and analysis of Configuration 0 were done using an Excel spreadsheet, whereas Configurations 1 and 2 were done first using Python scripts and then exported to Excel. Annual inflows were used as input data for the scripts, as well as the model parameters, which generated the annual material outflow time series in two separate files per configuration. The first one aggregated, which was used later for analysis, and the second one separating outflows by construction cohort, was kept for record and not used afterwards. The results were analysed in Excel for further calculations, processing, and visualisation. **Appendix B.2** presents the data integration and processing workflows applied in this analysis. Input data files, scripts and the resulting datasets are available in the SM (2.6-2.14).

2.3 Sensitivity analysis

To assess the robustness of the results to uncertainties in model assumptions, a sensitivity analysis was conducted by varying exclusively the mean service life of logistics buildings by ±15% and ±30% relative to the value adopted in Configuration 1. In all cases, lifetime was modelled as a truncated normal distribution between 30 and 120 years, with the standard deviation maintained as a fixed proportion (20%) of the mean. All other model settings were kept unchanged. The test was applied only to the probabilistic modelling configuration, as the deterministic case would only move the outflow curve in time without changing its shape. The Configuration 0 was therefore used primarily to locate ageing warehouses and centres, rather than to estimate future material flows.

The sensitivity analysis was implemented using the previously developed Python script, modified for this purpose, available as SM (2.15), with the resulting outputs analysed in Excel (SM 2.16-2.20). Results are presented in **Section 3.6**, with further justification in **Appendix C.1**.

3 Results

This chapter presents the results of the MSA, and subsequent MFA applied to commercial LCs in Santiago, Chile. The results describe the physical characteristics of the sector and quantify the spatial distribution, composition, and magnitude of material stocks, as well as their expected future outflows. Results are organised to reflect the main dimensions of the analysis. Together, these results provide a quantitative and spatially explicit basis for examining the UM potential of LCs, which is further discussed in the following chapter. **Sections 3.1** and **3.2** jointly establish the spatial and material basis for the analysis, while **Sections 3.3** and **3.4** address sub-research questions Q1–Q3 on stock magnitude, composition, and spatial distribution. **Section 3.5** addresses sub-research question Q4 by estimating when materials are expected to become available.

3.1 Logistics Sector Profile

Building on the logistics sector context described in **Appendix A.3**, this section presents the results of the spatial mapping and characterisation of LCs. The focus is placed on their location, spatial concentration, and physical characteristics.

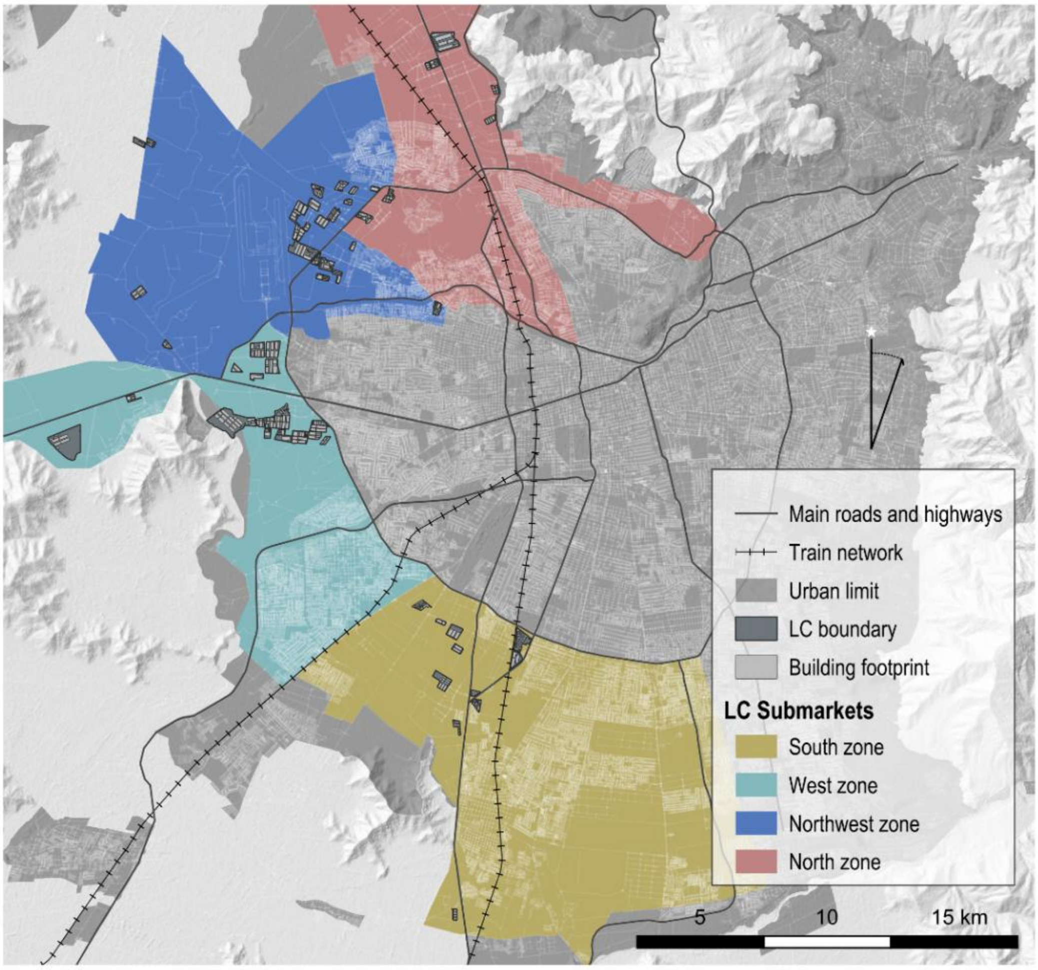

Figure 3. Spatial distribution of mapped logistics centres in relation to the main industrial submarkets of the Santiago Metropolitan Area.

Figure 3 shows that LCs are primarily located within specific industrial submarkets of the Santiago Metropolitan Area. A total of 65 LCs were mapped, corresponding to 24 different companies. These centres are in 9 out of the 52 municipalities of the Metropolitan Region. The three municipalities with the highest concentration of LCs are Pudahuel, Quilicura, and San Bernardo, together accounting for 76.9% of the total. Detailed information is provided in ***Table A. 3*** and ***Table A. 4***, within Appendix A. In terms of area, the mapped LCs cover a total of 1,137.0 ha, of which 535.0 ha correspond to warehouses and other buildings, 379.5 ha to paved surfaces, and 224.4 ha to open or green areas, representing 47%, 33%, and 20%, respectively. In the built-up areas, a total of 555 individual building footprints were identified and classified according to their typology. Detailed area distribution per LC is presented in ***Table A. 5***, within Appendix A. LCs have an average built area of approximately 82,000 m^2, with the largest reaching 430,000 m^2. After calculating the total built area, seven LCs were found to be below the initial 30,000 m^2 threshold; but were retained in the analysis since they had already been mapped and contribute to a more comprehensive spatial overview.

Figure 4. Examples of the three main warehouse types identified in the study area: (a) mini-warehouses, (b) ground-level warehouses, and (c) distribution centres. (Source: Google Maps (n.d.), accessed July 2025)

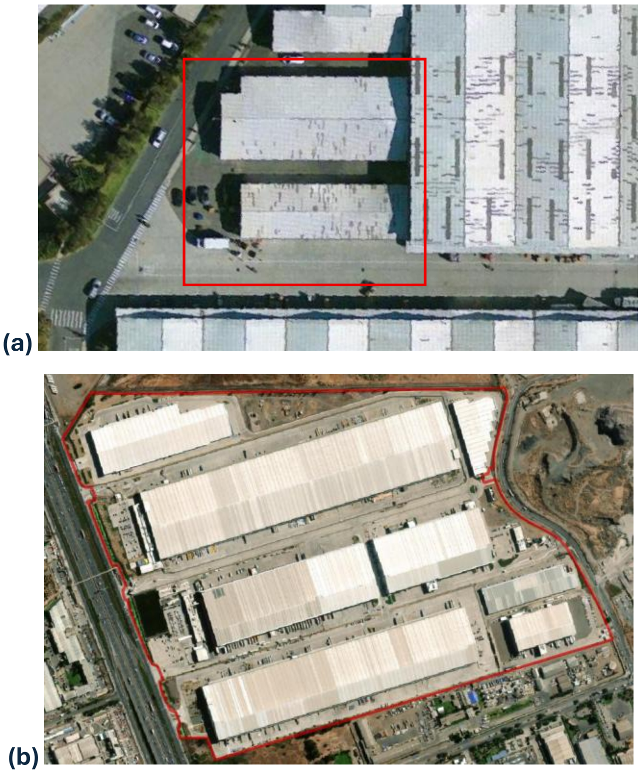

Figure 5. Contrast between warehouse scales: (a) mini-warehouses, and (b) a large logistics hall of approximately 100,000 m^2 within the Buenaventura logistics centre. (Source: Google Maps (n.d.), accessed July 2025)

In the sector, three main types of warehouses were identified: mini-warehouses, ground-level warehouses without elevated truck access, and distribution centres, as shown in ***Figure 4*** (a), (b), and (c), respectively. Regarding warehouse sizes, they range from small warehouse units, generally attached to larger warehouses or located between them to maximise land use (***Figure 5*** (a)), to large logistics halls of up to 100,000 m^2, as illustrated by ***Figure 5*** (b) showing the Buenaventura Logistics Centre, developed by Megacentro (MEC).

Most warehouses have fully open floor plans, while additional structures such as offices or bathrooms are usually added by tenants (see ***Figure 6*** (a), (b)). However, new developments increasingly incorporate these amenities from the start, as seen in ***Figure 6*** (c), which shows warehouses with integrated offices and client showrooms. Nevertheless, such examples remain rare within the mapped LC, where standard configurations are still predominant. A detailed catalogue is provided in the SM (1.6 and 1.7), illustrating the variety of warehouses and building identified. Less standardised solutions can also be found, developed under specific contractual agreements, commonly referred to as Built-to-Suit projects.

Figure 6. Examples of warehouse configurations: (a) and (b) standard warehouses with open floor plans, and (c) a new logistics development incorporating integrated offices and client showrooms within warehouse units. (Source: Google Maps (n.d.), accessed July 2025)

When examining the diversity of materials, a certain degree of standardisation can be observed in the types and uses of materials for roofs and roof structures, whereas walls, columns, and facades show greater variability. This variation is illustrated in ***Figure 7***. Despite these differences, concrete, steel, and masonry are the predominant materials within the LCs. The resulting typologies are described in the following section.

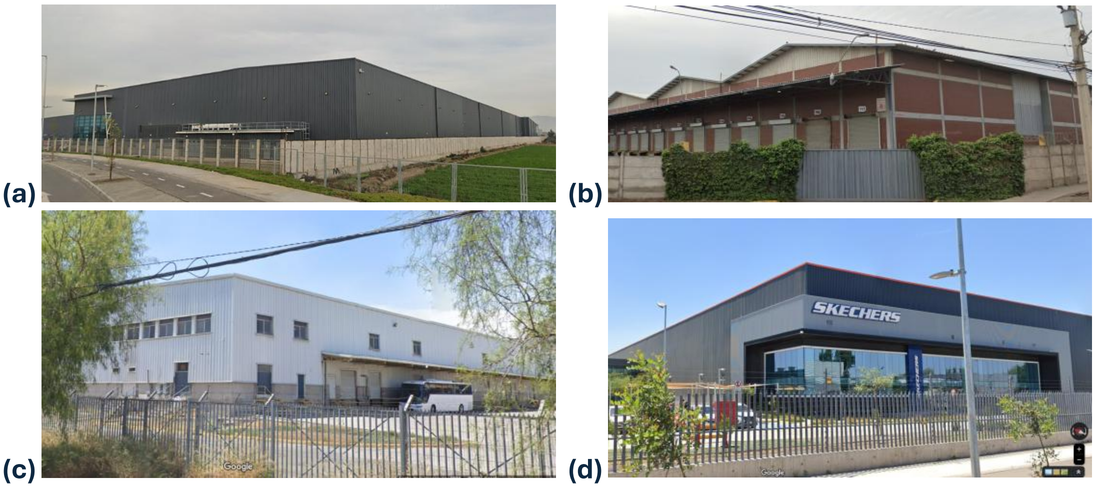

Figure 7. Examples illustrating the diversity of materials used in logistics centres, including metal, masonry, and concrete structures. (Source: Google Maps (n.d.), accessed May 2024)

3.2 Building Typologies and Material Intensities

Based on the preceding analysis, four main categories of warehouses were defined: mini, masonry, concrete, and steel. The last three categories were further subdivided according to their clear height: 6.5 m, 8 m, and 9.7 m for masonry; 8 m and 11.5 m for steel; and 8 m and 11.5 m for concrete. This classification follows sector standards and reflects common physical characteristics observed. Although some different configurations exist within the sector, the definition of eight typologies provides a balance between representativeness and practicality. It allows flexibility to adapt to the variety of warehouses found in Santiago's LCs while maintaining a manageable number of categories that ensures consistency and simplicity in both classification and subsequent analysis. Descriptions of the typologies are provided in ***Table 2***.

Structures, such as office buildings, light industrial sheds, or informal extensions, were excluded from the analysis due to their relatively minor representation within the sample and the limited information available on their material composition, which did not allow for the assignment of reliable MI factors. An example of this is shown in ***Figure 8***, corresponding to LC Huingán, which lacks visible structural definition and was therefore excluded from the results. In contrast, paved areas, although not initially considered in the research scope, were later included in the analysis due to their significant spatial extent and potential relevance to the overall MS. These areas were quantified as part of the MS assessment but analysed separately from the warehouses.

Regarding the construction characteristics of the assessed buildings, all typologies feature fixed joints commonly used in the sector, characterised by welded steel connections and other rigid joints between structural elements, as well as the extensive use of poured concrete. The most easily removable components are the metal wall and roof panels, which are typically bolted or screwed to the structural frame, allowing partial disassembly when required.

Table 2. Warehouse typologies and their main structural and material characteristics. Grouped typologies share identical structural configurations, differing only in clear interior height.

Typology name	Brief description	Typology code
Masonry WH: 9.7 m / WH 8 (grouped)	Confined masonry walls with reinforced concrete columns and beams, steel roof structure, and non-insulated metal cladding on roofs. Includes elevated truck docks on one or both sides; clear interior height: **9.7 m / 8.0 m**.	MW9.7 / MW8
Masonry WH: 6.5 m	Confined masonry walls with reinforced concrete columns and beams, steel roof structure, and non-insulated metal cladding on roofs. Direct floor-level truck access; clear interior height: 6.5 m.	MW6.5
Mini WH: 2.7 m	Self-storage modules with lightweight steel framing and non-insulated metal cladding on walls and roof. No concrete structural elements beyond the slab; clear interior height: 2.7 m.	MINIW2.7
Concrete WH: 11.5 m / 8 m (grouped)	Reinforced concrete frame (columns and beams) with steel roof structure and non-insulated metal cladding on walls and roof. Includes elevated truck docks on one or both sides; clear interior height: **11.5 m / 8.0 m**.	CW11.5 / CW8
Steel WH: 11.5 m / 8 m (grouped)	Steel structure with reinforced concrete walls and pillars at the loading dock area. Walls and roof are covered with non-insulated metal cladding panels supported by steel trusses and framing. Includes elevated truck docks on one or both sides; clear interior height: **11.5 m / 8.0 m**.	SW11.5 / SW8

Figure 9 compares the distribution of warehouse typologies by number and by total built area. The results show that 8-metre concrete warehouses (CW8) are the most common typology, representing 21% of all identified buildings and 24% of the total built area. When

grouped by construction system, concrete, masonry, and steel warehouses account for comparable shares of total buildings (29%, 27%, and 27%, respectively). In terms of built area, however, concrete warehouse typologies occupy a noticeably larger proportion, with 40% of the total, followed by masonry (34%) and steel typologies (24%). Detailed data per typology are provided in the SM (1.10).

Figure 8. Lightweight shed in LC Huingán illustrating a case excluded from the MI assessment.

The cumulative stock illustrates the steady expansion of warehouse floor area across the study period (***Figure 10***). After very limited growth in the 1980s and 1990s, a marked increase began around 1999, driven by the construction of 8-metre concrete warehouses (CW8). From 2005 onwards, the pace of development accelerated sharply, reaching its peak between 2013 and 2022, when the annual average reached 311,000 m^2 of new built area. By 2024, the total accumulated stock exceeded 5.3 million m^2, with 8-metre typologies, particularly CW8, MW8, and SW8, accounting for most of the built area. Detailed data per year and typology are provided in ***Table A. 7*** and ***Table A. 8*** (**Appendix A.5**).

Variations in the distribution of building typologies can be inferred from annual inflows, which allows understanding how the construction of different warehouse typologies has evolved over time. This temporal evolution is presented in ***Figure 11*** at the typology level and in ***Figure 12*** aggregated by structural category. For readability, both figures display the period 1992–2024, while the complete time series from 1977, together with the annual shares, is provided in **Appendix A.5**.

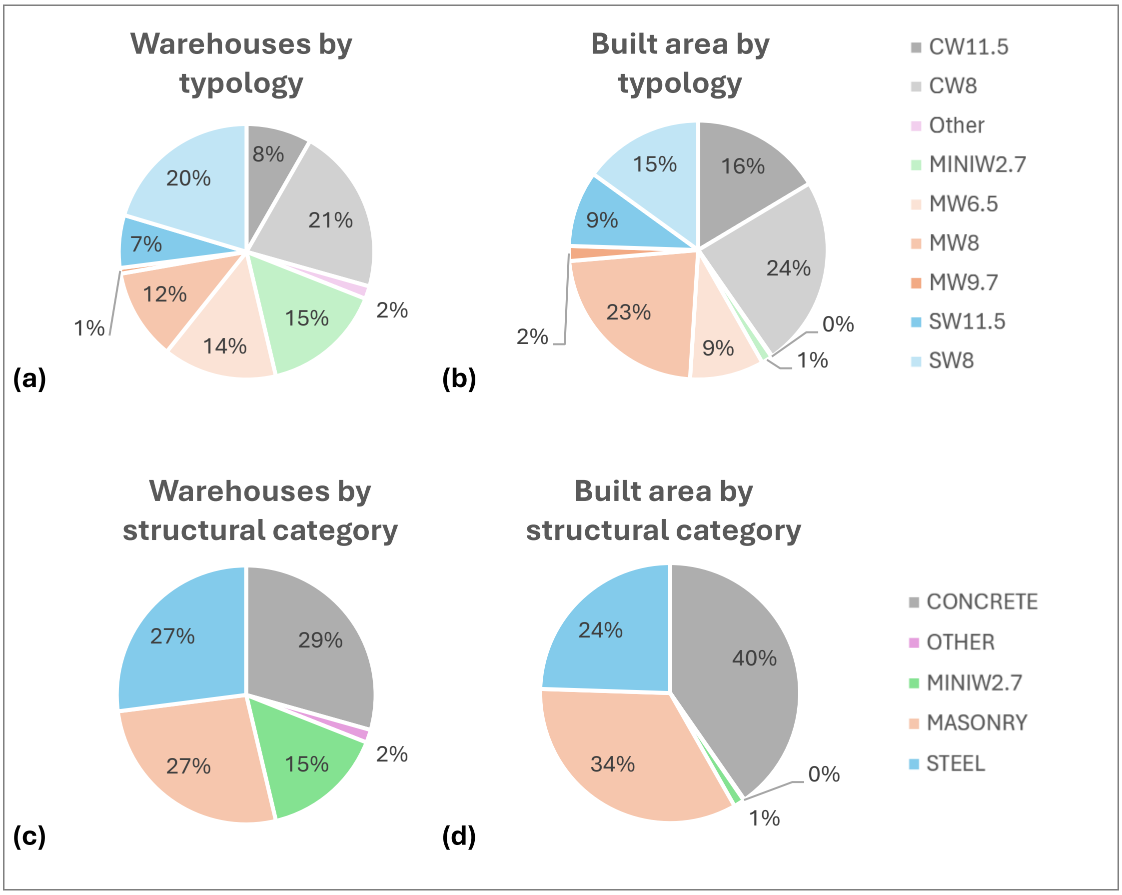

Figure 9. Distribution of warehouse typologies by number of warehouses and total built area, shown for detailed typologies (a–b) and aggregated structural categories (c–d).

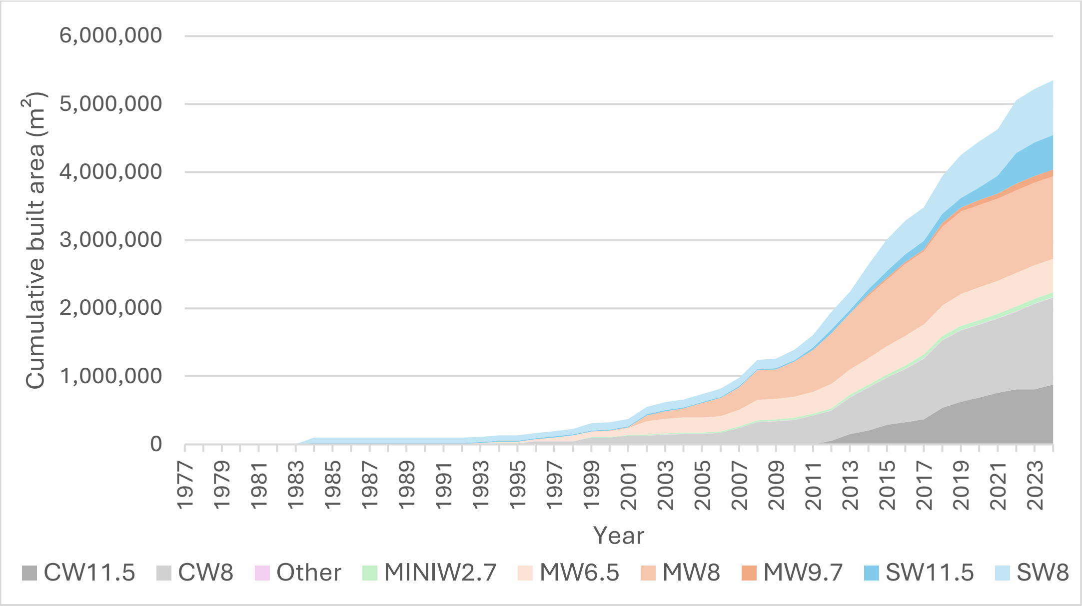

Figure 10. Cumulative built area stock of warehouse buildings by typology (1977–2024), expressed in square metres (m^2). The figure shows the progressive accumulation of total built area over time, derived from the annual additions per typology.

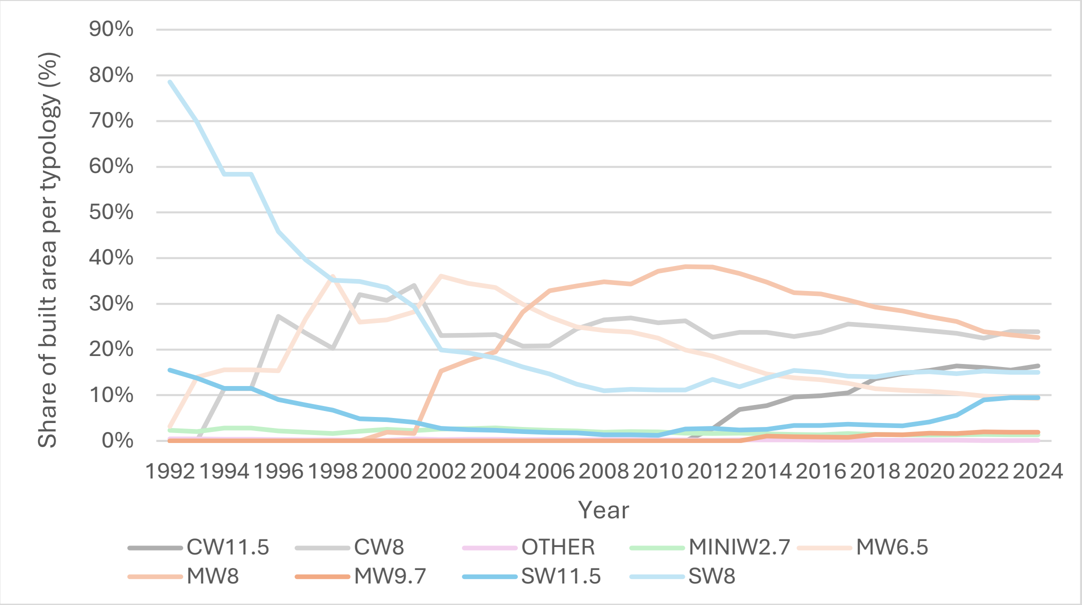

Figure 11. Share of built area by warehouse typology (1992–2024), expressed as a percentage of the annual stock surviving in 2024.

As ***Figure 11*** shows, in the 1992–2002 period there is high interannual variability, as the sector's stock is still building up and relative shares are sensitive during periods of limited accumulated stock. From 2002 onwards, year-to-year variations decrease and tend to stabilise towards the first quarter of the century. A noticeable trend is the steady decrease of the SW8 typology, which declines from nearly 80% in the early years to around 11% by 2010, ending in 2024 with approximately 15%. A similar trend is observed for the SW11.5 typology, which decreases from around 15% in the early years, and again around 2010 to just above 1%, before increasing to around 10% by 2024. In contrast, CW8 and MW6.5 are the typologies that show a sustained increase from 1992 onwards, with MW8 following a similar pattern but with a delayed expansion starting around 2002. In recent years, MW6.5 stabilises at close to 10% of the total stock, while CW8 and MW8 converge towards similar shares, both reaching approximately 23% by 2024. Typologies with a higher clear height, namely CW11.5 and MW9.7, appear later in the time series, becoming noticeable only after around 2013. Of the two, concrete-based warehouses show a more pronounced growth, with CW11.5 reaching approximately 16% of the total stock by 2024, whereas high-rise masonry warehouses (MW9.7) remain limited, accounting for only around 2%.

When analysing the evolution of built area aggregated by structural category, three characteristic periods can be identified. The first period, from 1992 to 2002, corresponds to a high variability phase, during which steel typologies decrease sharply in relative share, while concrete and masonry warehouses build up. By the end of this phase, masonry clearly dominates the sector, accounting for just over half of the total built area. From 2002 onwards, shares remain relatively stable among the three main structural categories, despite substantial growth in the sector, as the total stock increased by a factor of approximately 3.5 between 2002 and 2012 (see ***Table A. 7***). After this point, masonry steadily decreases from around 57% to approximately 34%, giving way to steel and concrete typologies, the latter becoming dominant by the end of 2024 with a share of around 40%. Self-storage typologies remain below 3% of the total throughout the analysed period.

It is important to note that shares are calculated relative to the total material stock surviving in 2024 and disaggregated by year of construction. This means that percentage values do not necessarily represent the full stock existing each year, but the portion that still remains in use in 2024.

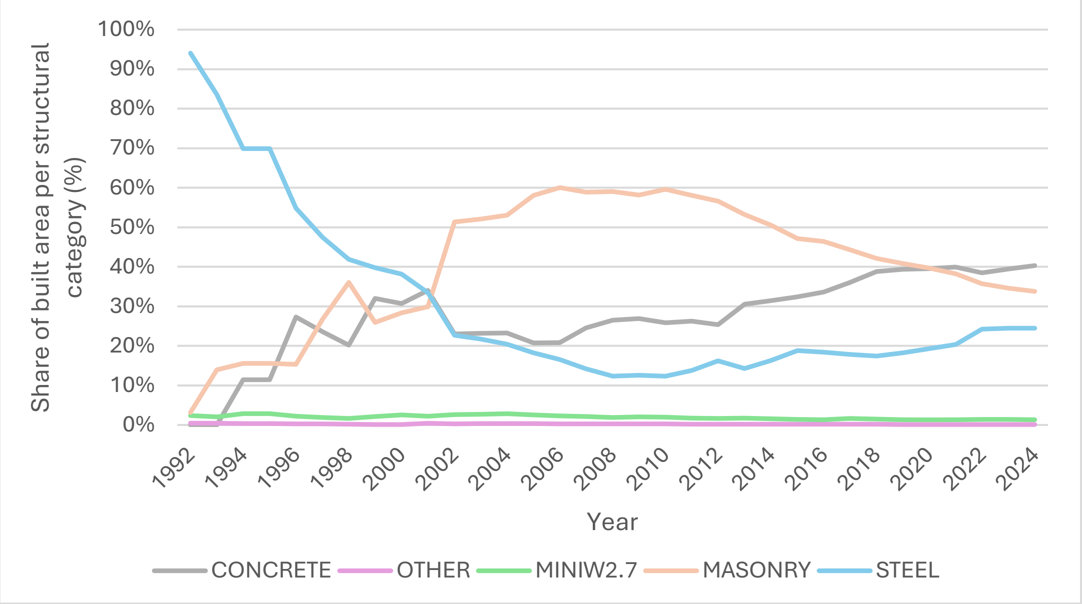

Figure 12. Share of built area by structural category (1992–2024), expressed as a percentage of the annual stock surviving in 2024.

Material Intensities

The calculated MI show the relative contribution of concrete, steel, masonry, mortar, and other materials across the eight typologies (see ***Figure 13***). At the aggregate material level, concrete accounts for most of the total intensity per typology, ranging between 91% and 94% per square metre. This predominance highlights concrete as a fundamental component of warehouse construction, used for pavements and base structures across all typologies, regardless of their primary structural system. Steel contributes between 2% and 8%, while masonry materials (bricks and mortar) are only present in the masonry warehouse typologies, where they reach 6–7% combined.

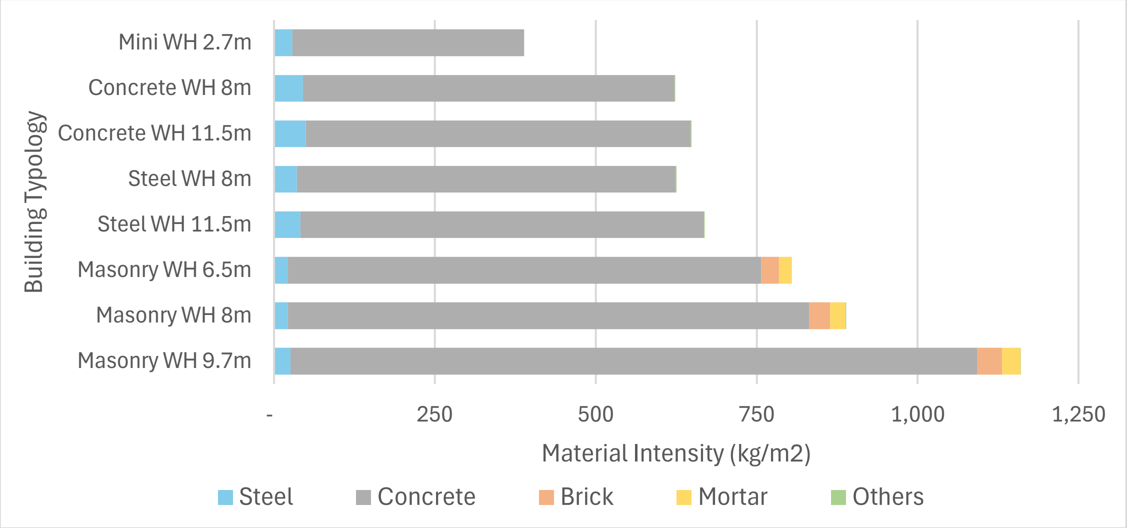

Figure 13. Material intensities (in kg/m^2) per typology of warehouses.

As shown in ***Figure 13***, masonry warehouses have the highest MI coefficients, ranging between 805-1,161 kg/m^2, considerably above other typologies. Steel and concrete warehouses show similar values for comparable height categories, with an average of 642 kg/m^2. Interestingly, the amount of concrete and steel within each structural typology behaves inversely to what might be expected: concrete warehouses contain less concrete than steel warehouses, and vice versa. This pattern results mainly from the reference buildings used to define the MI, which differ in their internal structural configurations. Nevertheless, the differences in total MI between concrete and steel warehouses are minor, with a variation of only 3.1% between CW11.5 and SW11.5, and 0.3% between CW8 and SW8. At the lower end of the range, self-storage modules reach 388 kg/m^2, representing approximately 61% of the average MI of steel and concrete warehouses. This relatively high intensity, considering their smaller height, is largely explained by the use of similar concrete floors structures, as illustrated in ***Figure 14***, where materials are categorised by component.

A comprehensive overview of MI at both the material and component levels, together with variable definitions and coding explanations, is provided in ***Table A. 11-Table A. 14***, within **Appendix A.5**. Complete calculations, underlying assumptions, and additional information on the reference buildings are available in the SM (1.8).

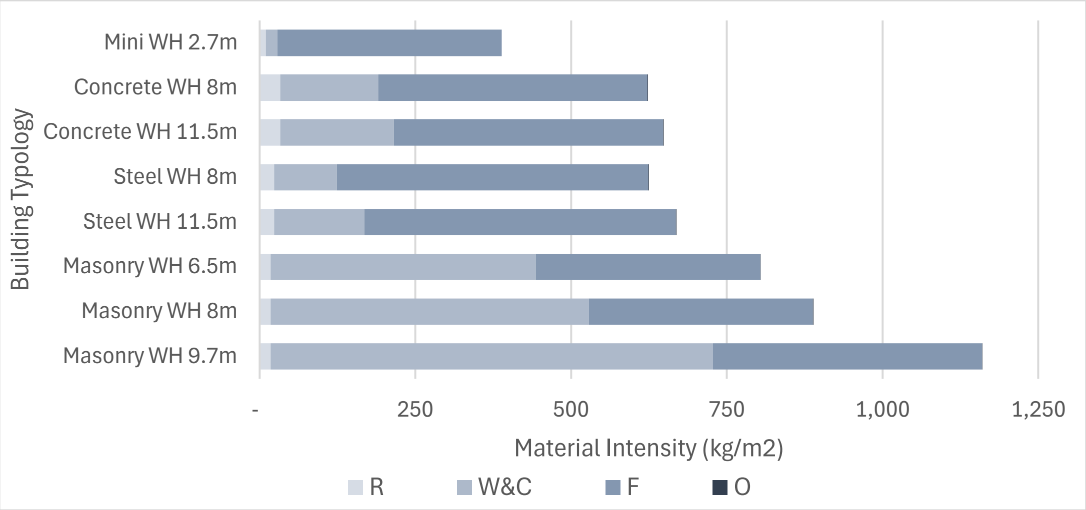

Figure 14. Material intensities (in kg/m^2) by component group (R: Roof; W&C: Walls and Columns; F: Floor; O: Others) across warehouse typologies.

Specifically, for paved areas within LCs, 15 cm-thick concrete slabs with no reinforcing steel mesh were assumed, following the configuration used by the largest company in the sector (Bodegas San Francisco). The same concrete density previously adopted for all warehouse typologies (2,400 kg/m^3) was applied, ensuring consistency across all concrete-related calculations. This characteristic does not affect the previously presented MI values for the warehouses, as it refers to the common areas of the LCs and not to the interior of the buildings. This yields an MI for paved areas of 360 kg/m^2, which is only 7% lower than that of the self-storage unit.

3.3 Material Stocks

This section presents the quantified MS embedded in LCs across Santiago, addressing sub-research questions Q1 and Q2, and providing a temporal and compositional overview of their evolution. MS were quantified by combining the MI defined in **Section 3.2** with the total built-up and paved areas of each LC. The results represent the total quantity of materials embedded within Santiago's LCs as of 2024, distinguishing between warehouse buildings and paved areas. Warehouses account for 74% of the total MS (3.83 million tonnes), while common paved areas represent the remaining 26% (1.37 million tonnes), as illustrated in ***Figure 15***. It is worth noting that the 1.37 Mt of paved areas consist entirely of concrete, whereas the remaining 74% correspond to the distribution of warehouse typologies and their respective MI factors.

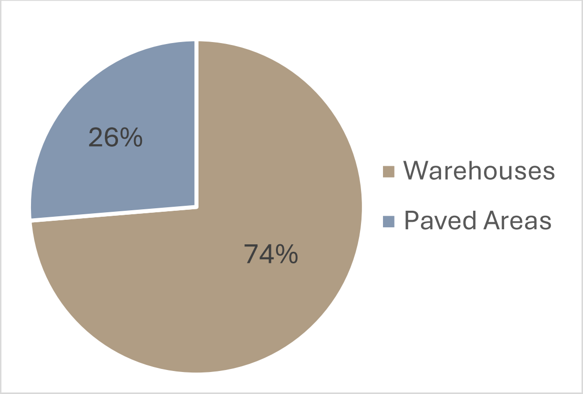

Figure 15. MS distribution for the logistics sector in Chile's Metropolitan Region.

The evolution of material inflows and accumulated stocks reveals how the sector in Santiago has developed over the past four decades. ***Figure 16*** shows the annual material inflow by material type, while ***Figure 17*** and ***Figure 18*** present the cumulative MS, first by material category and then by typology. Together, these figures describe the temporal dynamics and composition of the current stock. The coding system used for the presented graphs is provided in ***Table A. 11***.

As shown in ***Figure 16***, material inflow remained relatively low until the late 1990s, after which construction activity increased steadily. From the mid-2000s onwards, significant year-to-year variations can be observed in material use, reflecting a flexible sector strongly influenced by client-specific contracts. The observed peaks in inflows are mainly associated with the completion of large warehouses or clusters of warehouses within a few LC. For instance, the 2008 peak corresponds to construction in only three LC, which together accounted for nearly 80% of the 201,000 tonnes entering that year. Since 2005, excluding the year following the subprime crisis, annual inflows have consistently exceeded 50,000 tonnes, reaching a maximum in 2018 with almost 330,000 tonnes added to the stock. The period between 2013 and 2022 marks the most intensive phase of development, coinciding with the consolidation of large-scale LC. Throughout the entire study period, concrete consistently dominates the inflow, followed by steel, while masonry materials and others play only a minor role. This persistent dominance of concrete aligns with the limited variation in its share among the defined typologies.

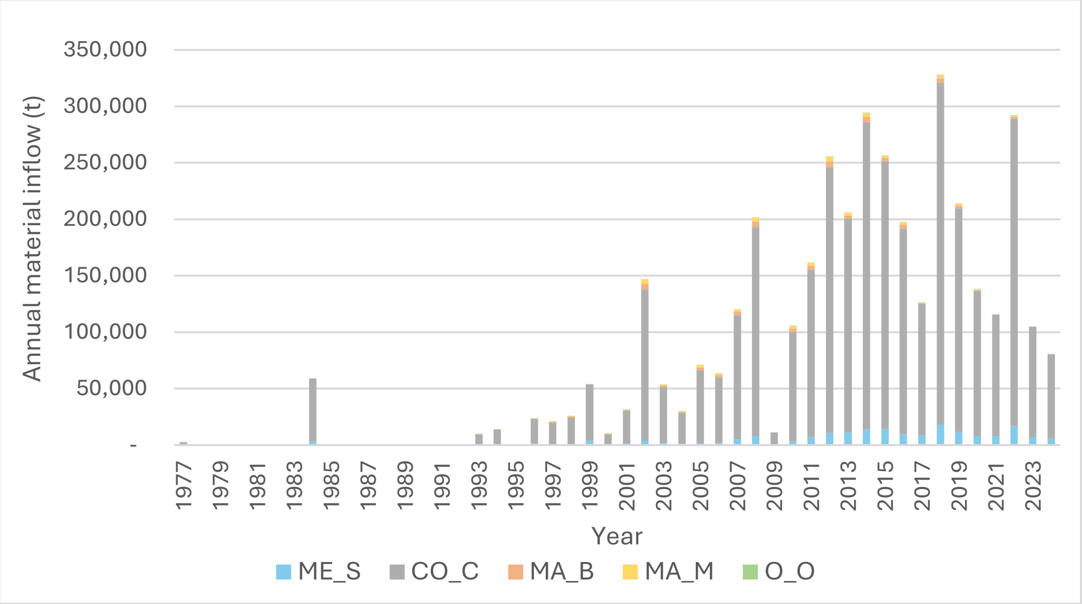

Figure 16. Annual material inflow by material (1977–2024), expressed in tonnes (t). The figure shows the total quantity of materials for warehouses entering the logistic sector each year.

As shown in ***Figure 17***, the cumulative MS has increased steadily over the study period, reaching its current composition summarised in ***Table 3***. Concrete represents approximately 92% of the total accumulated stock by 2024, with over 3.5 million tonnes. The second-largest materials are steel and bricks, accounting for about 5% and 2%, respectively, while mortar and other minor materials together contribute less than 1.5%. This demonstrates the sector's reliance on concrete for construction and the limited material diversity for its operation.

Table 3. MS of warehouses in LC in Santiago (2024), by material category.

Material	Material Stock (t)	Share (%)
Concrete	3,531,900	92.3%
Steel	190,826	5.0%
Masonry Brick	57,551	1.5%
Masonry Mortar	41,442	1.1%
Others	5,017	0.1%
Total	**3,826,737**	**100%**

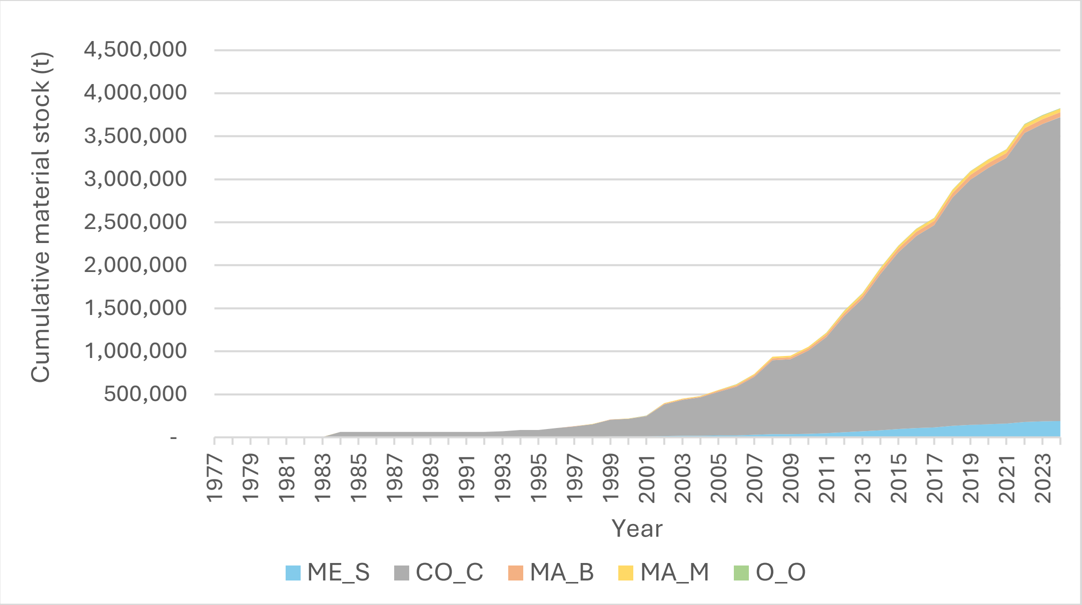

Figure 17. Cumulative MS in warehouses by material (1977–2024), expressed in tonnes (t). The figure shows the accumulation of materials over time.

Figure 18 presents the cumulative MS by structural typology. Unlike the results in ***Figure 10***, where CW8 accounted for the largest share of built area, this figure shows the actual relevance of MW8 typology in terms of material use. The three dominant typologies: MW8, CW8, and SW8 account for roughly two-thirds of the total stock. This reflects the higher MI of masonry warehouses, due to the confined concrete and brick structure, which result in greater material demand despite similar heights.

The MS were plotted over time to show how materials accumulated by year of construction. The analysis does not consider removals or demolition events before the cut-off year. Therefore, the resulting curves should be interpreted as cumulative and non-decreasing representations of the MS.

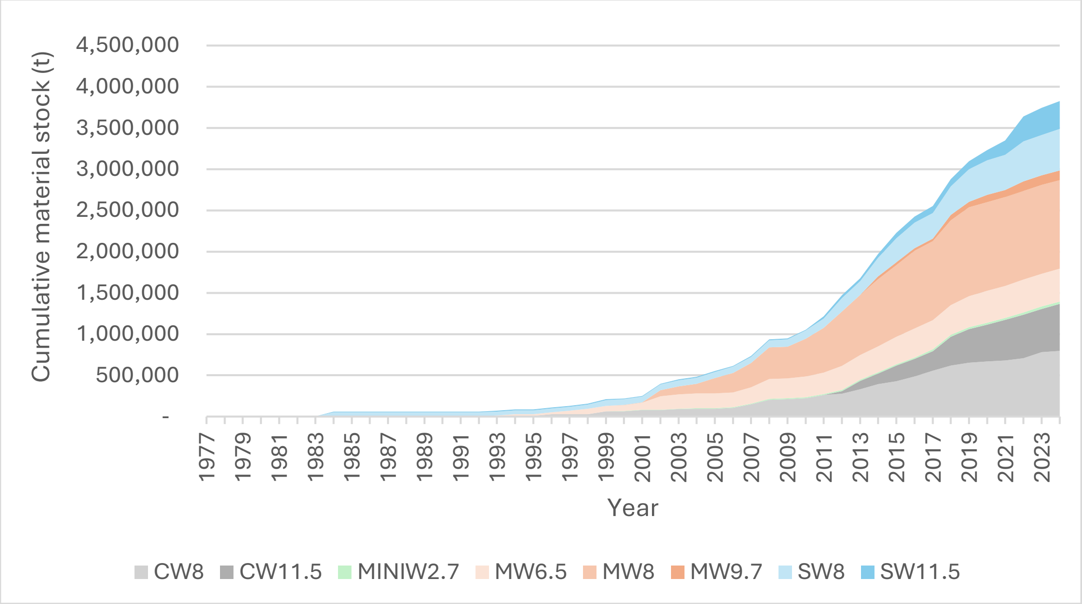

Figure 18. Cumulative MS by warehouse typology (1973–2024), expressed in tonnes (t). The figure shows the accumulation of materials according to their corresponding typology.

Building on the historical evolution of MS, ***Figure 19*** shows how the stock is distributed between companies and within them by typologies. The results reveal a highly uneven distribution of material ownership in the sector, with only a few companies concentrating a substantial share of the total stock. In fact, the largest operator alone accounts for almost 40% of the sector's embedded material, and together with the next two companies represents nearly two thirds of the total. These differences are explained by two factors. On the one hand, differences on the total built area per company, as presented in ***Table A. 5***. On the other hand, average MI values per company (see ***Figure A. 11***), resulting from construction choices.

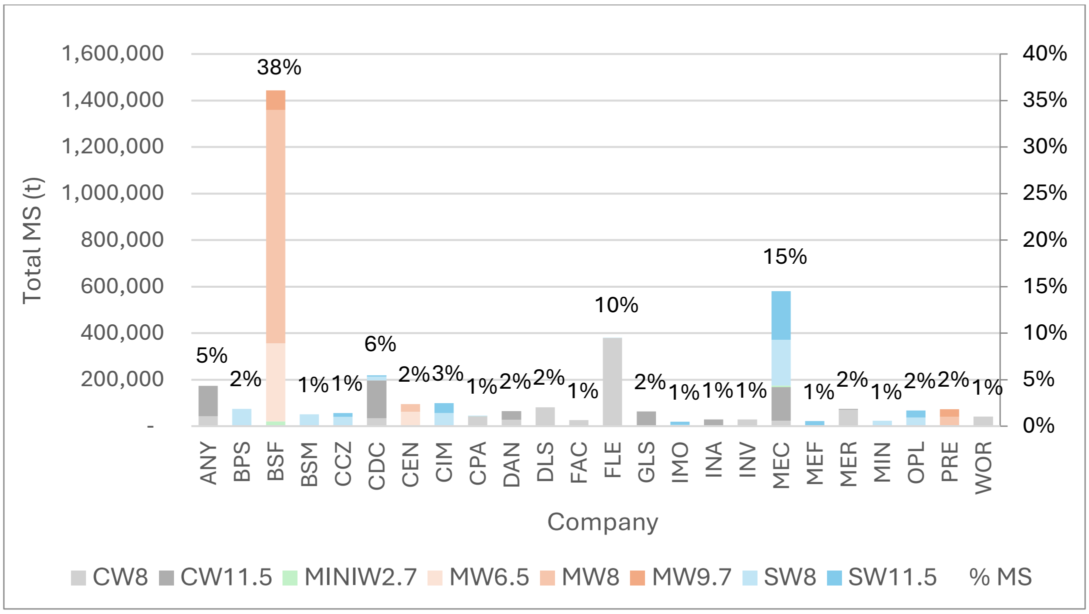

Figure 19. Total MS by company and typology, expressed in tonnes (t). Paved areas within each LC are not considered in these values.

Finally, ***Figure 20*** show how the 3.8 million tonnes of materials are distributed across the different components. Floors account for the largest share, followed by walls and columns, while roofs and other parts represent a smaller portion. This helps to understand how materials are spread within warehouse structures, valuable when identifying recovery options.

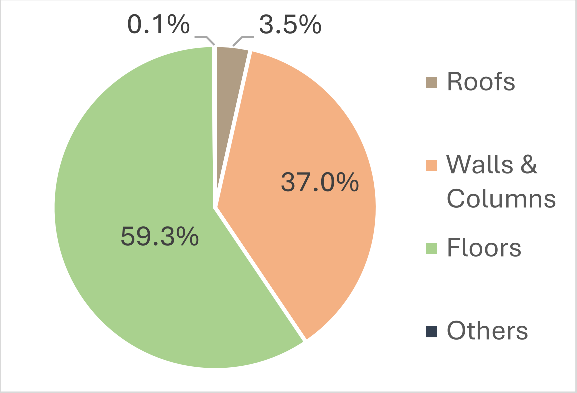

Figure 20. Distribution of materials by component group, expressed as a share of the total material stock (3,826,737 t). Roofs (134,409 t), Walls and Columns (1,417,115 t), Floors (2,270,195 t), and Others (5,017 t).

Overall, this section describes the magnitude and composition of materials found in Santiago's LCs. Concrete dominates, and most materials are concentrated in a few typologies, so the sector shows little variation in construction systems. Additional figures and detailed tables supporting these results, including annual inflows and total stocks, as well as the distribution of stocks and MI among companies, can be found in **Appendix A – Material Stock Accounting**. Additional data are available in the SM main calculation file (SM 1.10). The following section looks at how these MS are distributed across the Metropolitan Region, identifying areas of accumulation and potential relevance.

3.4 Spatial Distribution of Material Stocks

This section addresses sub-research question Q3 by presenting the spatial distribution of MS across Santiago's LCs, identifying geographical patterns of accumulation and how this varies among municipalities and companies.

Figure 21 depicts the spatial distribution of MS by warehouse within Santiago's LCs in 2024. The map reveals a high degree of clustering across the metropolitan area, with most LCs concentrated in the north-western and western sectors of the city. As expected, MS per warehouse increases within larger centres, where extensive plots allow the development of bigger halls, while smaller centres display correspondingly lower values. The most substantial concentrations are located in the western submarket, where the two largest LCs in terms of total MS contain individual warehouses reaching up to 36,000 tonnes. However, the single warehouse with the highest MS is located in the northern submarket, containing approximately 76,000 tonnes. Together, the western and north-western LCs shape the main locations for logistics activities, outside Américo Vespucio highway and nearby Route 68.

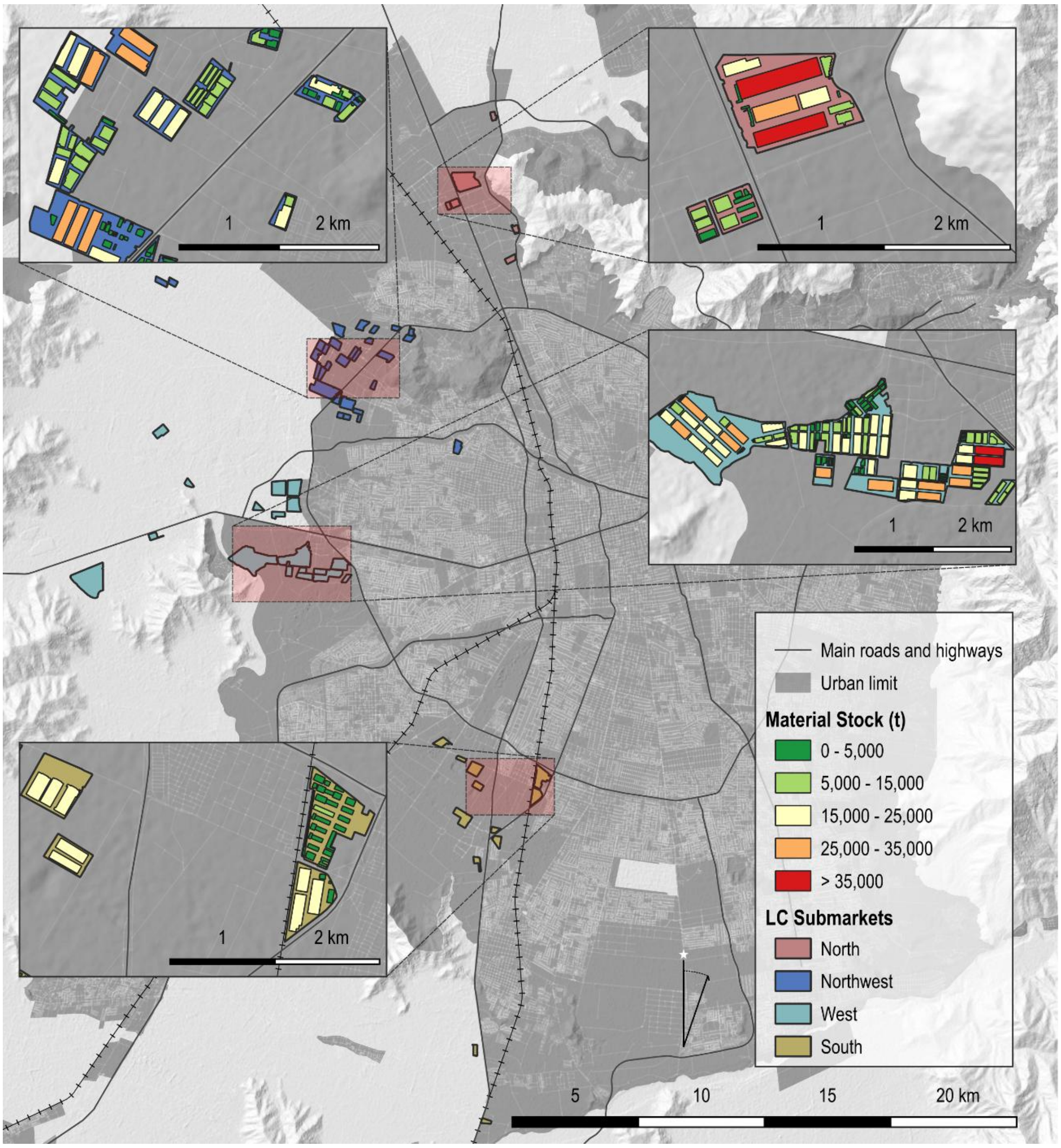

Figure 21. Spatial distribution of MS by warehouse within Santiago's LC in 2024, showing the four submarkets and their main clusters of warehouses. The colour scale represents the relative stock magnitude per building, expressed in tonnes (t).

Figure 22 summarises the total MS per LC, integrating both built and paved areas. Compared to the distribution by warehouse shown in ***Figure 21***, this map highlights that only a small number of centres concentrate a substantial proportion of the total materials of the sector. In fact, just 9 of the 65 LC account for nearly half of the total MS. Most LCs fall within the lower ranges (< 80,000 tonnes), while a few large-scale LC exceed 160,000 tonnes (detailed information in ***Table A. 21***, within Appendix A). These high-stock centres are predominantly located in the western zone of Santiago, confirming the spatial dominance of large logistics hubs in those areas.

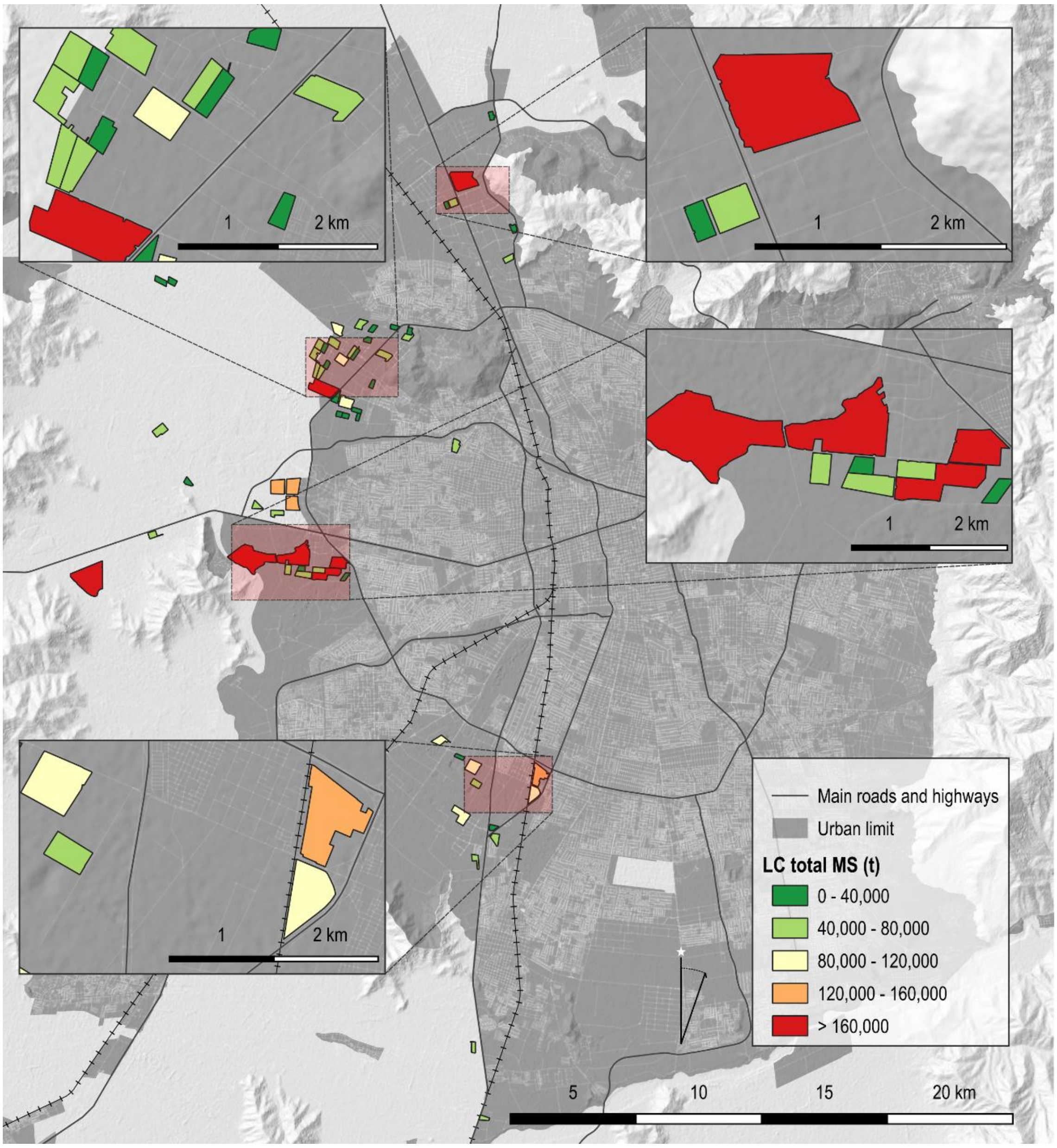

Figure 22. Spatial distribution of total MS by LC within Santiago in 2024, including both built and paved areas. The colour scale indicates the cumulative MS of each LC, expressed in tonnes (t).

Mapping MS at the municipal level allows a more contextualised understanding of how materials are spatially distributed across the study area, which is essential for identifying local conditions that may favour or constrain future UM initiatives. ***Figure 23*** presents total and density values of MS by municipality in Santiago. Pudahuel shows a markedly higher total MS, exceeding 3 million tonnes, followed by San Bernardo with approximately one fifth of that amount. At the other end of the range, Cerro Navia records the lowest total MS, with less than 50,000 tonnes. In terms of material density, Lo Espejo and Pudahuel exhibit similar values, both around 16,000 t/km^2, followed by Renca with over 10,000 t/km^2. ***Table 4*** summarises these results, distinguishing between warehouses and paved areas.

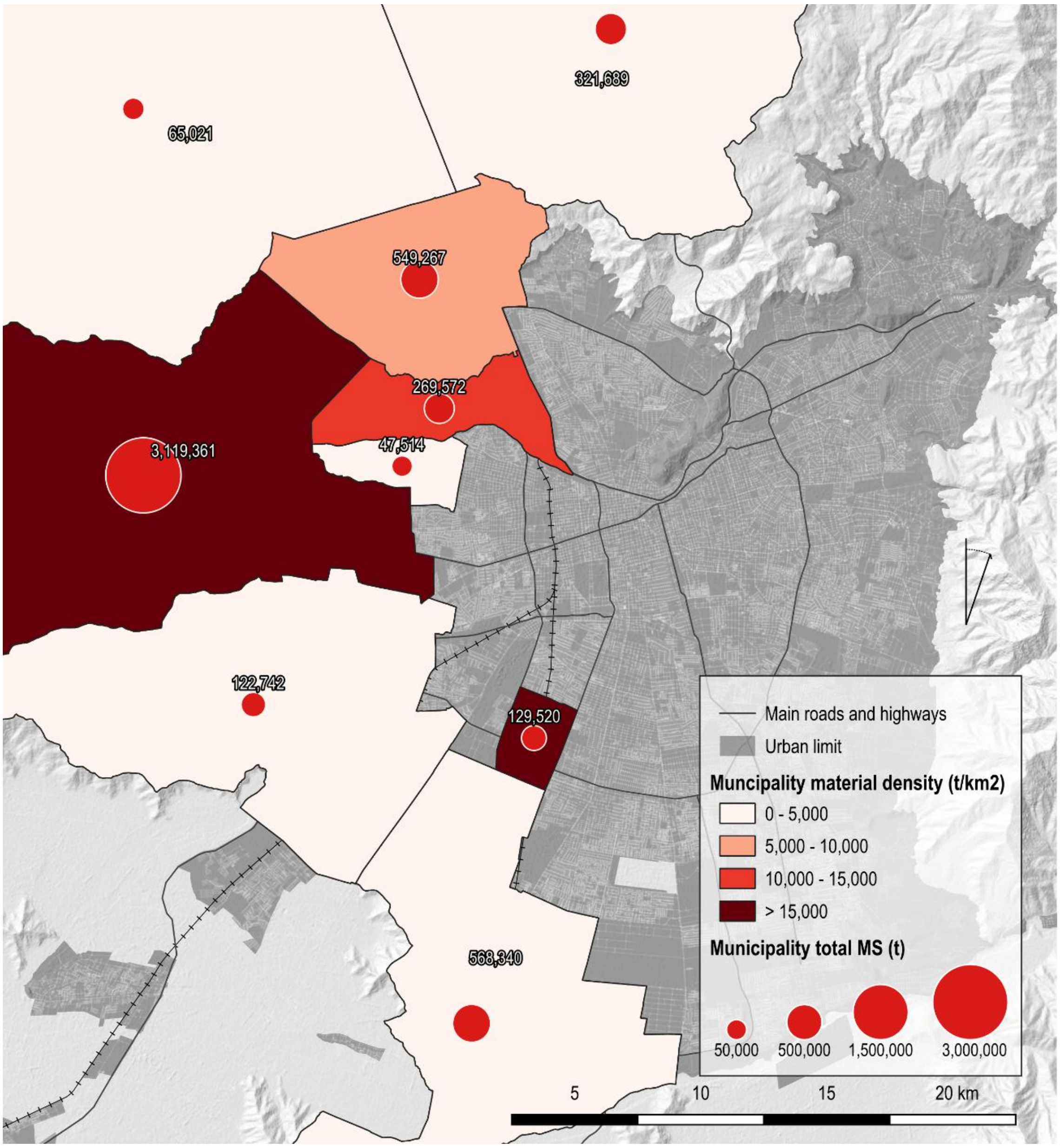

Figure 23. Spatial distribution of total MS by municipality within Santiago in 2024, including both built and paved areas. Circle size represents the total MS (t), while the colour scale indicates the MS density (t/km^2).

When analysing the historical development of the sector, the construction year of each LC was reviewed to identify potential temporal or spatial trends. The results show a relatively homogeneous development across the different submarkets, at least the LCs that still operate by 2024. ***Table A. 23*** in Appendix A presents the weighted average construction year of each LC, calculated from the individual warehouses within each centre. This value was also used to assign a representative construction year to each centre's paved areas. These results serve as a reference point for the following analysis on future material availability.

Table 4. Distribution of MS by municipality in 2024, including both built and paved areas. MS density is expressed in tonnes per square kilometre (t/km^2).

Municipality	WH (t)	PA (t)	Total MS (t)	MS density (t/km^2)
QUILICURA	402,716	146,552	**549,267**	9,580
PUDAHUEL	2,359,047	760,314	**3,119,361**	15,813
SAN BERNARDO	419,723	148,617	**568,340**	3,717
MAIPÚ	97,363	25,379	**122,742**	891
RENCA	178,663	90,909	**269,572**	11,346
LAMPA	43,780	21,241	**65,021**	144
COLINA	223,057	98,632	**321,689**	331
CERRO NAVIA	28,745	18,769	**47,514**	4,281
LO ESPEJO	73,645	55,875	**129,520**	15,718
Total	**3,826,737**	**1,366,289**	**5,193,025**	**2,584**

3.5 Future Availability of Material Stocks

Building upon the quantified stocks and their spatial distribution, this section examines future material availability over time and space, specifically addressing question Q4. Three modelling choices are used to explore how different lifetime representations and inflow aggregation levels shape the temporal and spatial patterns of future material outflows.

3.5.1 Spatial patterns of future material availability

Overview of spatial distribution

Spatial patterns were examined using the deterministic lifetime configuration (60 years), which allows the identification of individual warehouses. While this approach provides only an indicative estimation of timing, it enables a spatial view of where outflows may occur.

Figure 24 presents the expected decade of material availability for individual warehouses across Santiago, indicating the logistic submarket they serve. The map shows clear spatial clusters. Warehouses within the same logistics centre, and sometimes within the same submarket, often have similar expected outflow decades. This is due to shared construction periods within each centre, which create similar EOL timelines for neighbouring warehouses. Nevertheless, a few centres differ from this pattern. As shown in ***Figure 25***, the three selected examples display expected outflows spread across four decades, based on the lifetime configuration used for this spatial analysis.

Table 5 summarises the total outflows per decade, showing that most availability is expected after 2060 under the assumed lifetime configuration, with a pronounced peak between 2070–2079. In turn, less than 6% of the stocks are expected to be available before year 2060. ***Table B. 1***, in Appendix B, presents the disaggregation of Table 5, showing material outflows at component level for each decade.

Table 5. Expected material outflow per decade using a fixed 60-year lifetime, in tonnes (t).

Decade	Total outflow (t)	Decadal contribution (%)
2030-2039	2,491	0.1%
2040-2049	59,043	1.5%
2050-2059	147,844	3.9%
2060-2069	739,198	19.3%
2070-2079	2,146,623	56.1%
2080-2089	731,537	19.1%

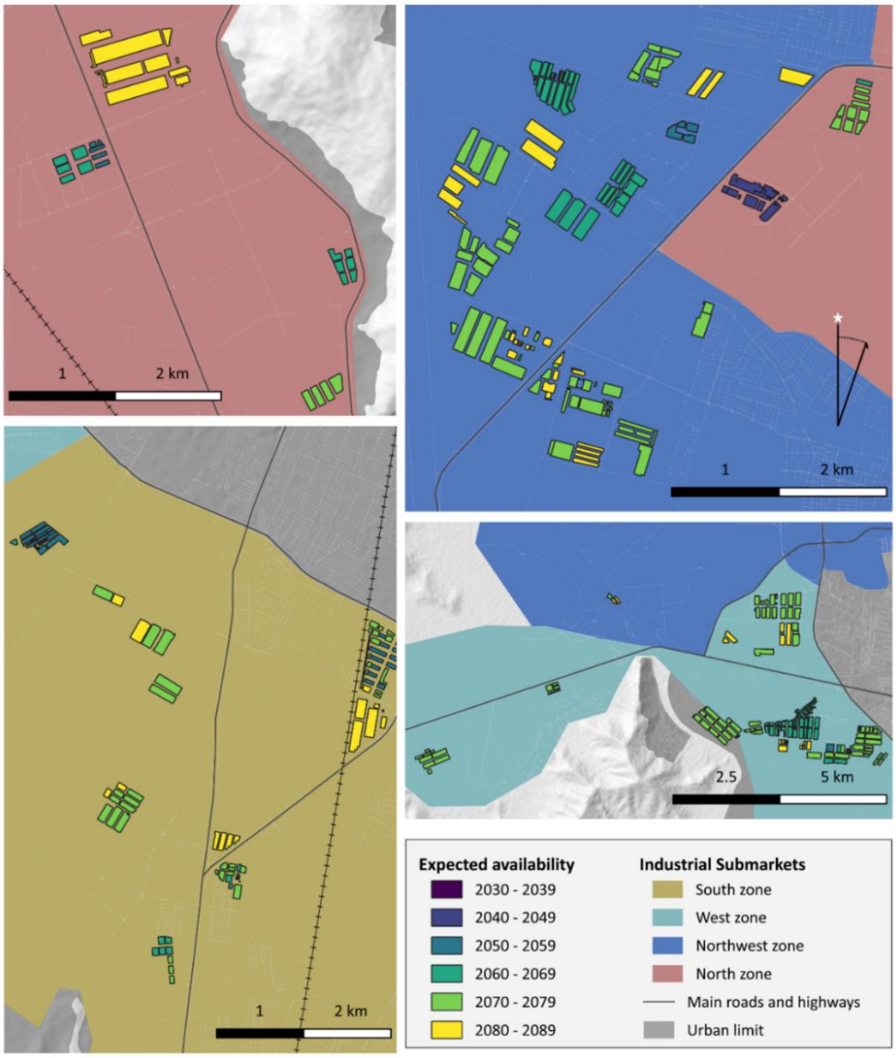

Figure 24. Expected decade of material availability from logistics centres in Santiago, grouped by industrial submarket.

Municipal concentration of material availability

After looking at patterns at the warehouse, the analysis now considers the municipal scale to show where outflows may concentrate across Santiago. ***Figure 26*** shows the distribution of expected material availability aggregated by municipality across the coming decades. The first two decades (2030–2050) show very limited activity, with outflows appearing only in Maipú, Quilicura and Cerro Navia. ***Table 6*** complements ***Figure 26*** by showing the total outflows per municipality and decade, together with the number of warehouses reaching EOL. The difference between the material outflow in ***Table 6*** and the MS reported in ***Table 4*** for two specific municipalities is explained in **Appendix B.4**. However, it reflects a shift in allocation, and the overall total remains the same.

From 2050 onwards, outflows start to appear in additional municipalities, including Pudahuel and Lo Espejo. From 2060 onwards, the flows increase sharply and concentrate mainly in Pudahuel, Quilicura and San Bernardo. The highest expected availability occurs in Pudahuel during 2070–2079, with almost 1.4 million tonnes of materials from 284 warehouses. Although outflows decrease in 2080–2089 to levels similar to the 2060–2069 decade, they still exceed 700,000 tonnes, with Pudahuel and Colina showing the highest expected availability.

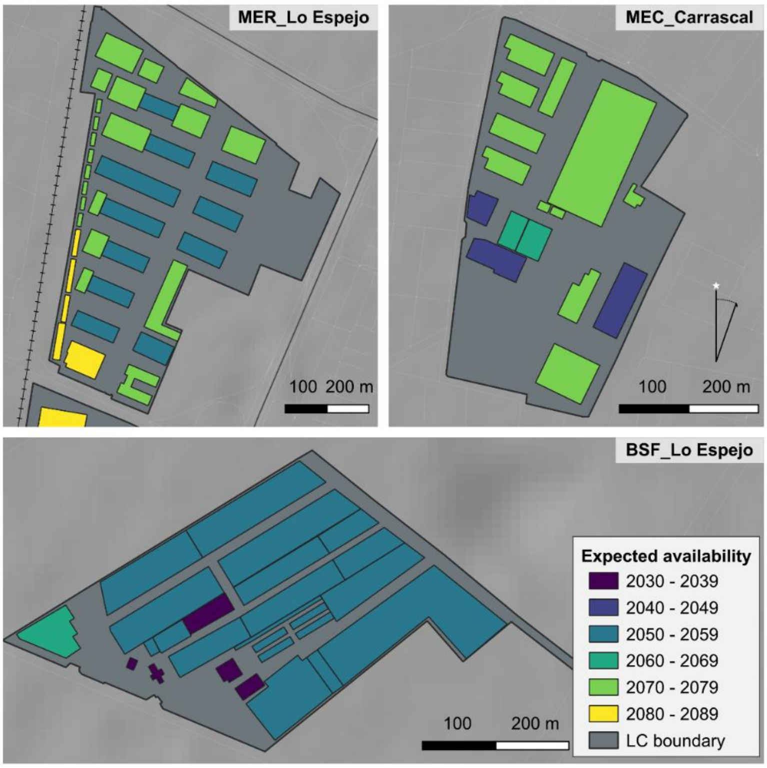

Figure 25. Example of LC with wider variation in expected material availability.

To contextualise these results, the pavements within LCs are not included in the spatial analysis. The fixed-lifetime configuration assigns outflows to warehouse units, to represent individual building EOL rather than complete centre renovation. For detailed information supporting this section, see the SM (2.1).

Table 6. Expected material outflow per municipality and decade, with the number of warehouses reaching end of life. Outflows expressed in tonnes (t).

Municipality	**2030-2039**	**2040-2049**	**2050-2059**	**2060-2069**	**2070-2079**	**2080-2089**	**Total material outflow(t)**
QUILICURA	-	54,268	30,795	150,709	120,822	46,123	**402,716**
PUDAHUEL	-	-	18,746	553,251	1,393,883	309,305	**2,275,185**
SAN BERNARDO	-	-	-	30,440	259,306	129,977	**419,723**
MAIPÚ	2,491	-	64,182	2,690	111,862	-	**181,225**
RENCA	-	-	-	-	143,262	35,400	**178,663**
LAMPA	-	-	-	-	39,947	3,832	**43,780**
COLINA	-	-	-	-	22,122	200,934	**223,057**
CERRO NAVIA	-	4,776	-	2,108	21,861	-	**28,745**
LO ESPEJO	-	-	34,121	-	33,557	5,966	**73,645**
Total material outflow (t)	**2,491**	**59,043**	**147,844**	**739,198**	**2,146,623**	**731,537**	**3,826,737**
Warehouses per decade	**5**	**18**	**41**	**125**	**284**	**82**	

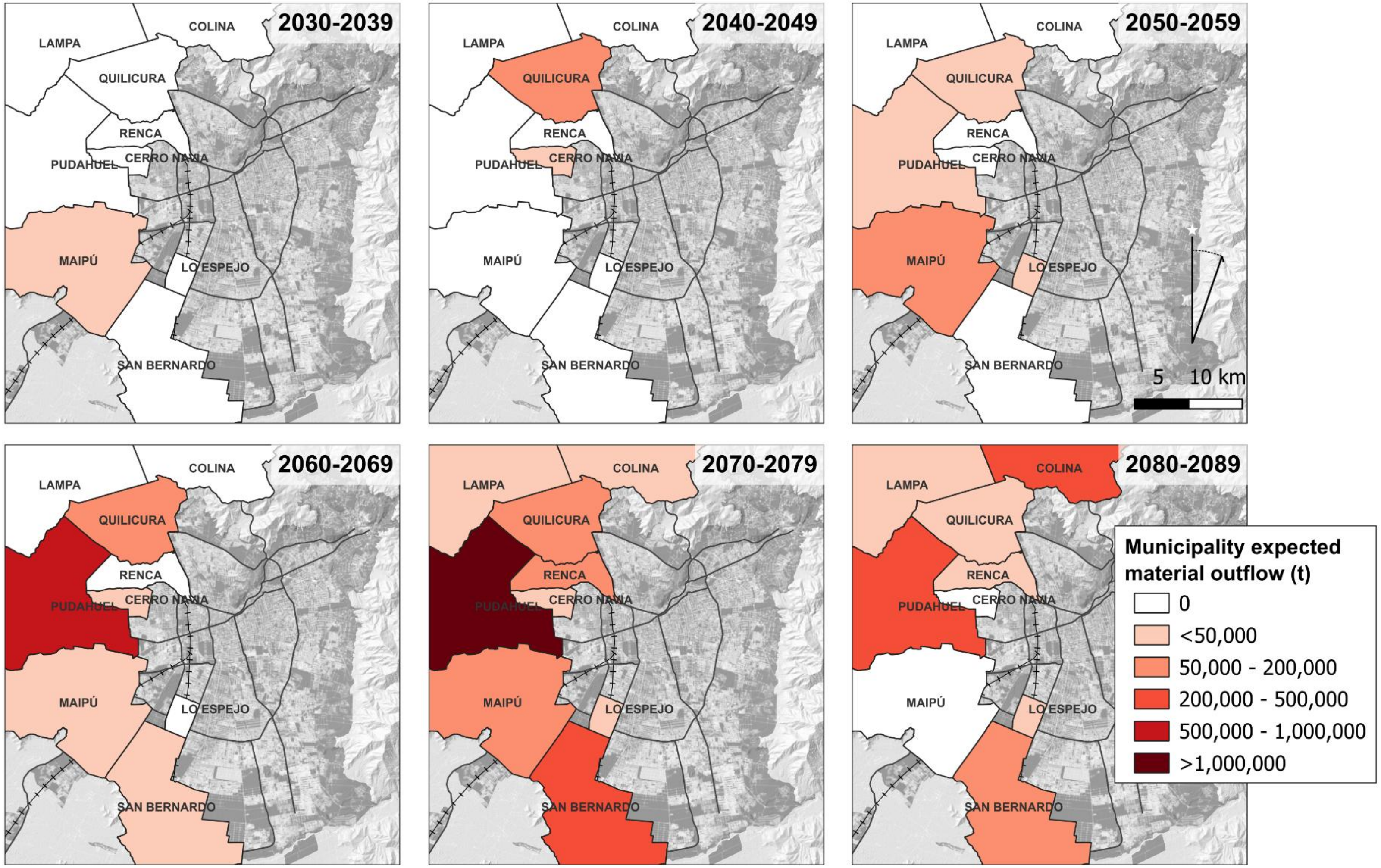

Figure 26. Spatial distribution of expected material availability aggregated by municipality over the coming decades, expressed in tonnes (t). Only municipalities with logistics centres from the study are shown.

3.5.2 Temporal dynamics of future material availability under probabilistic lifetimes

Building on the spatial results obtained under the fixed-lifetime assumption, this section examines the temporal dynamics of future material availability using probabilistic lifetime distributions.

Overview of probabilistic modelling and configuration choice

Two probabilistic modelling configurations were developed to estimate future material outflows. The first applies a lifetime distribution at the individual warehouse level, using disaggregated construction years as inflows, whereas Configuration 2 aggregates inflows at the logistics-centre level and includes shared external paved areas. Although the inflow time series differ, the resulting outflow curves show nearly identical temporal behaviour.

To support the characterisation of future material availability that is likely to enter EOL management pathways, Configuration 1 is adopted as the main representation in this section. It focuses on materials within individual warehouse structures, including interior slabs, while excluding shared external pavements that are typically retained in situ during redevelopment. Configuration 2 provides a complementary representation based on aggregated inflows at the LC level and is documented in **Appendix B.5**, where the implications of inflow aggregation for outflow dynamics are examined.

Temporal distribution and composition of future material outflows

Under probabilistic lifetime assumptions, material outflows remain very limited until around 2040, after which they increase progressively, reaching a maximum around the mid-2070s before declining over several decades (as shown in ***Figure 27***).

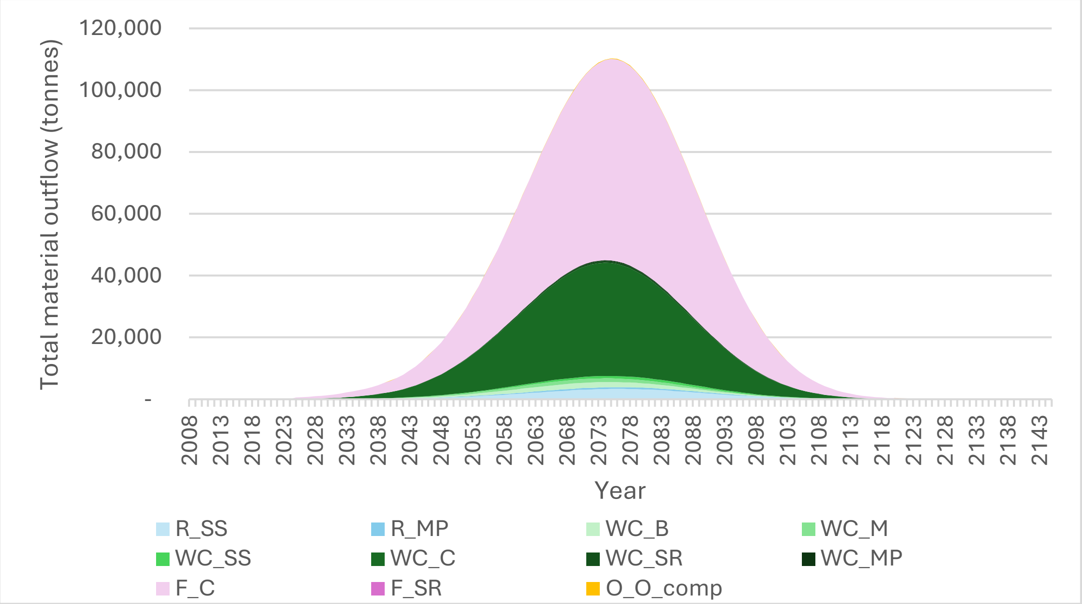

Figure 27. Annual material outflows by component under Configuration 1 (2008-2145), expressed in tonnes (t).

The stacked curves show that, while differing in magnitude, all material components follow a similar temporal pattern, with their highest releases concentrated within the same period. As such, these results represent aggregated probabilistic outflows rather than discrete demolition events. Annual and decadal values reflect the distribution of EOL probabilities across the existing stock and indicate when material availability is expected to be highest at the sector level. Detailed annual outflow values underlying ***Figure 27*** are reported in Appendix B (***Table B. 4***).

To facilitate interpretation, outflows are aggregated at a decadal scale in ***Table 7***. This aggregation is used to show long-term trends in material availability, smoothing short-term variability. As shown in this table, material availability increases rapidly from the 2040s onwards, with the highest outflows occurring between 2060 and 2089. Together, these decades account for approximately 72% of the total projected material releases, indicating a strong temporal concentration of future material availability from the existing 2024 stocks.

In contrast, material releases in the short term remain limited. Over the next 15 years, less than 1% of the initial stock is expected to become available, corresponding to under 35,000 tonnes. The resulting evolution of the remaining MS is shown in ***Figure 28***, illustrating the cumulative effect of the projected outflows over time. The detailed composition of outflows by material and component at the decadal level is reported in Appendix B (***Table B. 6***).

Table 7. Decadal aggregation of projected material outflows under probabilistic lifetimes, expressed in tonnes (t).

Decade	Total
2000-2009	-
2010-2019	-
2020-2029	4,201
2030-2039	29,409
2040-2049	122,643
2050-2059	392,149
2060-2069	815,854
2070-2079	1,078,019
2080-2089	861,222
2090-2099	400,841
2100-2109	105,686
2110-2119	15,435
2120-2129	1,226
2130-2139	52
2140-2149	1

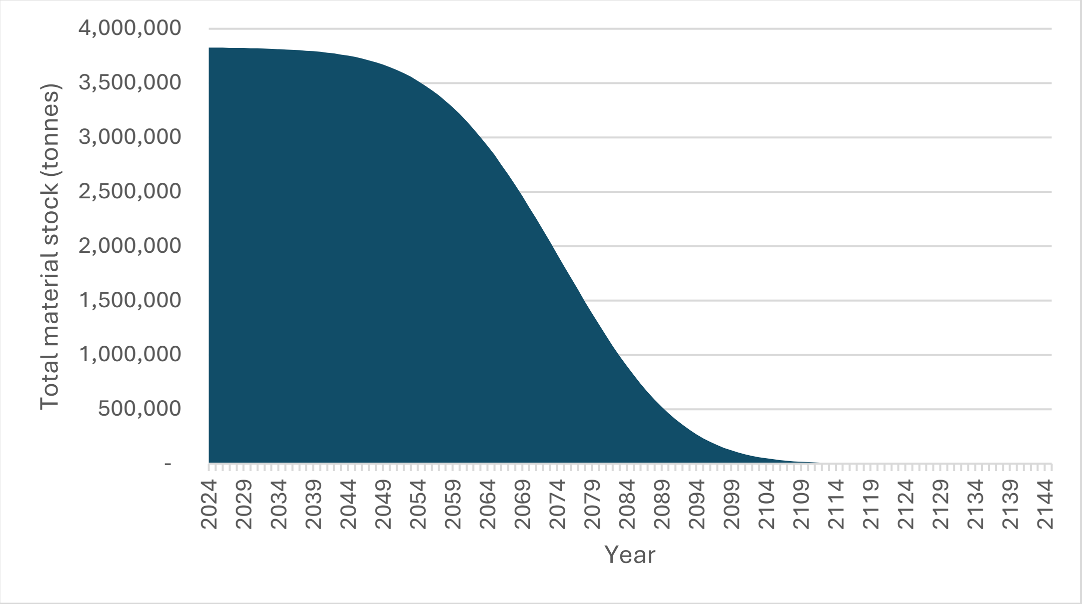

Figure 28. Remaining material stock under Configuration 1 (2024–2145), expressed in tonnes (t).

3.6 Sensitivity analysis

Due to the limited availability of reliable and context-specific data for several key inputs, it is necessary to assess how uncertainties in model assumptions influence the previous results. The sensitivity analysis therefore focuses on the input parameter that both shapes the previous results and present the highest degree of uncertainty: the assumed service life of logistics buildings. The justification for this choice is further discussed in **Appendix C.1**.

Temporal shifts and distribution of material outflows

Changes in the assumed mean lifetime lead to a clear temporal shift in future material outflows. Shorter lifetimes result in earlier releases, while longer lifetimes delay sector's material availability by several decades. As shown in ***Figure 29***, reducing the mean lifetime by 30% results in the highest material outflows occurring shortly after mid-century, whereas increasing the mean lifetime to 78 years postpones peak material availability to the end of the century.

As shown in ***Table 8***, changes in the assumed mean lifetime not only shift the timing of material outflows but also affect how much material is released per year. When the mean lifetime decreases, outflows become more concentrated, leading to higher annual release rates. This is the consequence of the direct relationship between the mean and the standard deviation, which increases the steepness of the outflow curve for shorter lifetimes. As a result, shorter service life concentrates material release into fewer decades, while longer lifetimes distribute outflows over longer time spans.

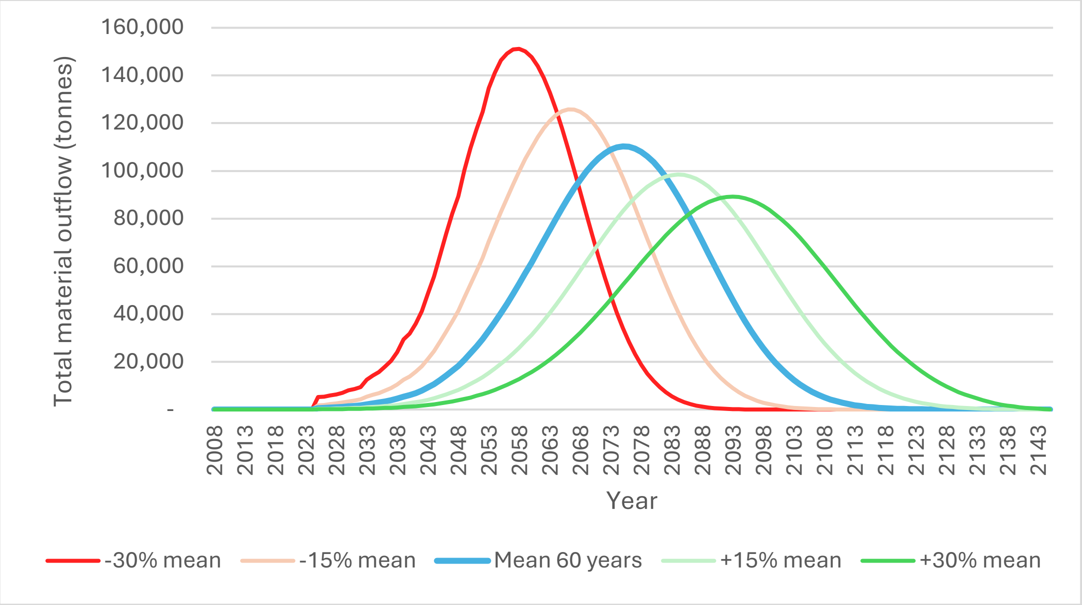

Figure 29. Sensitivity analysis of future material outflows, expressed in tonnes (t).

In the most extreme cases analysed, 50% of the total stock is released within approximately 13 years in the -30% case, compared to around 24 years in the +30% case. For the -15% and +15% cases, these effects are less pronounced but remain relevant. This is illustrated by examining the last five decades of the modelling period, during which total outflows in the -15% case do not exceed 7,000 tonnes, whereas the central case exceeds 122,000 tonnes over the same period. In **Appendix C.2**, ***Table C. 1*** shows the unaggregated expected material outflows for each of the cases analysed in this section.

Table 8. Sensitivity analysis: expected material outflows aggregated by decade under different mean lifetime assumptions, expressed in tonnes (t).

Decade	Mean 60 years	+15% mean	-15% mean	+30% mean	-30% mean
2000-2009	-	-	-	-	-
2010-2019	-	-	-	-	-
2020-2029	4,201	1,624	11,361	680	29,855
2030-2039	29,409	12,458	69,646	5,502	160,349
2040-2049	122,643	54,832	279,708	25,375	623,231
2050-2059	392,149	187,423	791,358	90,794	1,375,208
2060-2069	815,854	460,834	1,210,459	245,371	1,189,321
2070-2079	1,078,019	807,486	983,763	508,445	399,813
2080-2089	861,222	967,542	397,917	783,194	47,177
2090-2099	400,841	770,395	75,783	875,921	1,764
2100-2109	105,686	399,540	6,498	699,931	19
2110-2119	15,435	132,914	242	395,084	0
2120-2129	1,226	27,978	4	155,061	0
2130-2139	52	3,563	0	38,660	0
2140-2149	1	149	0	2,719	0

4 Discussion

Based on the results presented previously, this section discusses the key findings and implications, placing the results in context and clarifying their relevance. It also assesses the validity and limitations of the research and outlines recommendations.

4.1 Key findings

Material stocks embedded in LCs are highly concentrated spatially within industrial zones in the Metropolitan Region. A small number of municipalities and a limited set of LCs account for a disproportionate share of the total stock. Roughly half of the stock is embedded in just eleven large LCs (≈17% of all centres), with the two largest located in the western area. This highlights the strongly clustered nature of material accumulation associated with warehousing infrastructure within the logistics sector.

Regarding the size of the stocks, the total amount accounted for over five million tonnes of material, with most of it embedded in warehouse buildings. However, due to the characteristic layout of LCs, shared paved areas should not be taken for granted, as they account for approximately one quarter of the total MS.

In terms of the types of materials present, the sector is characterised by very low material diversity, with only a small number of materials used across it. Concrete overwhelmingly dominates, accounting for approximately nine out of every ten tonnes of material used in the sector, while steel and masonry account for a minor share. Concrete is present across all major building components, including foundations, columns, beams, and internal floor slabs. At the component level, floors alone host close to 60% of the total MS and are entirely composed of concrete, while in other components this material still dominates.

Material stock accumulation in LCs is relatively recent and has accelerated since the mid-2000s, with no clear indication of slowing down within the observed period. Under the service life assumptions adopted in this study, most materials are expected to remain in use for several decades, resulting in limited short-term availability, with peak material releases projected for the 2070s.

Although several warehouse typologies were defined, the sector presents a high degree of standardisation in layouts, structural systems, and material use, with many typologies corresponding to variations of a limited number of structural systems. This degree of standardisation allows MS in LCs to be accurately described in terms of recurrent construction systems rather than individual buildings. At the same time, MI can still vary substantially. In particular, 8-metre warehouse typologies, despite having the same clear height, present MI differences of up to around 50%. Similar patterns are observed in remaining typologies, indicating that construction choices play an important role in determining material demand.

4.2 Implications of the results for urban mining in logistics centres

This section discusses the main implications of quantified stocks in logistics centres for UM, considering their availability under current conditions.

Understanding the urban mining potential of the logistics sector

Based on the existing warehouse stock and its assumed service lives, the UM potential of LCs is predominantly long-term. The recent expansion of the sector results in limited near-term material availability, with material release projected to increase only as the stock matures. A single pronounced peak is expected, reflecting the relatively concentrated construction history of the sector and leading to a temporally focused release profile rather than multiple or flattened peaks. As a result, the potential contribution of secondary materials to primary material substitution in the short term is likely to remain limited, despite the large size of the existing stock.

Building on the projected material outflows, a potential contribution of recovered materials to future construction needs within the sector can be estimated. Under a simplified representation of historical construction flows to support stock expansion, the analysis detailed in **Appendix B.6** suggests a theoretical substitution potential of approximately 19% of future primary material inflows from 2025 onwards. If recovered materials were hypothetically reintroduced into future logistics centre construction, they could partially offset new material requirements. This estimate should be interpreted as a highly exploratory upper bound, intended to illustrate orders of magnitude rather than feasible or near-term substitution outcomes.

Given the continued growth of the sector (Colliers, 2025; Cushman & Wakefield, 2025), total MS are likely to expand beyond the values quantified in this study (2024 reference year), and therefore the long-term UM potential estimated here. By contrast, the high degree of standardisation in construction practices suggests that the material composition of stocks and, by extension, of their outflows is likely to remain stable in the future.

The projected outflows reflect the probability distribution of EOL of the existing stock and should be understood as an indication of when material availability is expected to be higher at the sector level, rather than as exact dates of warehouse decommissioning.

Initially, the analysis focused on mapping the stocks of large LCs, corresponding to approximately 80% of the total logistics warehouse floor area. However, industry reports suggest that the quantified area represents almost 95% of the total logistics warehouse surface in the Santiago Metropolitan Area, thereby providing a highly representative picture of the regional stock (Cushman & Wakefield, 2025). Beyond considerations of stock coverage, the stock estimates in this study represent the maximum extractable urban ore that could, in principle, become available over time. Thus, values presented here do not account for technical, regulatory, economic, or organisational aspects that ultimately define actual recovery and future use of materials. In this sense, transforming MS into meaningful inputs for reuse or recycling requires a detailed characterisation, as presented in this study, but also appropriate feasibility assessments of their exploitations, as highlighted by Cheng et al. (2018).

Implications for material recovery conditions and practices

A comprehensive interpretation of the results is constrained by the limited availability of local data on material consumption and in-use stocks in other sectors. Nevertheless, the findings allow for the identification of key implications. By focusing on a single NRB sector and developing sector-specific typologies, this study provides a higher level of resolution, enabling component-level analysis with sector-wide relevance. In doing so, it contributes to existing UM research in Chile, where academic work remains scarce despite its relevance. This is shown by the recent work of Ozturk (2025), which evaluates the MS recovery potential of photovoltaic modules. The study estimates future waste quantity and composition, informing policy and resource management strategies while offering insights into associated environmental and socio-economic impacts. However, such stock-oriented research remains uncommon, and recovery actions targeting urban material flows have mainly focused on municipal solid waste and comparatively short-lived stocks, such as electronic devices, largely driven by the implementation of the Extended Producer Responsibility law (Cayumil et al., 2021; Vargas et al., 2021).

While MFA results show a smoother aggregate outflow profile at the sector level, material availability is expected to occur as discrete events rather than continuous flows. This behaviour is further reinforced by the spatial clustering of commonly owned buildings, meaning that EOL decisions are likely to occur at the level of entire centres rather than individual buildings. These characteristics therefore need to be considered in the design and assessment of future material management and treatment systems.

Despite the existence of significant MS, current material management practices suggest that the system is not well prepared for their recovery. According to Fundación Chile (2020) the construction sector in Chile lacks standards for waste management, reporting requirements, obligations for waste segregation or valorisation, and adequate infrastructure relative to the volume of flows generated. This hinders the translation of material availability into actual recovery under present conditions. As a result, most construction materials are not recovered and are disposed of in landfills or, in some cases, illegal dumping sites (Construye2025, 2020; Ministerio del Medio Ambiente, 2024; Ossio & Faúndez, 2021). However, the results of this study indicate that most materials embedded in LCs will only become available over the long term, particularly when compared with other contexts where warehouse stocks are considerably older and remain in operation (Schebek et al., 2017).

The temporal gap between future material availability and current management capacities provides an opportunity to define recovery objectives and support anticipatory planning, particularly in relation to policy frameworks addressing construction and demolition waste management. Although UM is not explicitly addressed in Chile's Circular Economy Roadmap to 2040, several actions target waste generation and material recovery, including technical standards to improve demolition practices and facilitate the use of recycled materials (Initiative #7) and infrastructure development for C&D waste valorisation (Initiative #26) (Ministerio del Medio Ambiente, 2021). These actions aim to contribute to the 75% recycling target set for 2040. If recycling capacity development explicitly includes construction materials rather than being limited to municipal-like solid waste streams, this target would be broadly aligned with the expected timing of material outflows from LCs. In parallel, C&D Waste Strategy directly addresses the construction sector, including targets for nationwide recovery infrastructure (Axis 1) and requirements to incorporate recycled materials in public infrastructure projects (Axes 2 and 3), which, if effectively implemented, could enable the management of expected material releases from LCs. However, some objectives remain broadly defined, such as the 2025 target under Axis 4 to establish national CE indicators for construction, without clarifying how these indicators would be operationalised or used to guide material management decisions (Construye2025, 2020).

Beyond timing considerations and existing practices, the material composition of the stocks and the physical characteristics of buildings also condition the feasibility of recovery options once materials become available, as highlighted by Wallsten et al. (2015). LCs mapped in this study exhibit a relatively low diversity of construction materials compared to other NRB sectors (Ortlepp & Deilmann, 2015; Schebek et al., 2017). However, MI values may still vary across otherwise comparable buildings due to differences in construction choices, highlighting the importance of using sector-specific factors. The strong dominance of concrete implies that future material availability will be largely concentrated in a high-volume but comparatively low-value material stream. While the recovery of steel from C&D waste streams is generally considered economically viable (Ghisellini et al., 2022), the material composition observed in the studied sector is likely to reduce recovery incentives, at least for recycling, with steel representing less than 5% of the total stock.

Existing recovery options remain limited, with only a few actors, such as Río Claro in the northern Metropolitan Region, accepting construction and mining waste to produce recycled aggregates, generally when a specific end-use or project is already secured. A similar pathway could be defined for masonry structures. However, recent updates to technical standards regulating the use of recycled and artificial aggregates in concrete (e.g. NCh163:2024) are likely to improve their incorporation in new construction (Maldonado, 2024). By contrast, steel recycling is more established in Chile, with actors such as AZA, the country’s main producer of recycled steel, operating in the Metropolitan Region, which facilitates the recovery of steel from LCs (AZA, 2024).

LCs are characterised by simple design features compared to other sectors, with standardised layouts and repetitive structural systems that reduce material variability. This structural simplicity, observed across dominant typologies, can facilitate material separation at EOL, particularly for steel structures and metal cladding, which are typically used as independent elements and can be more easily separated from other components. As a result, they offer more favourable conditions to be reclaimed and reused than other material systems. However, moving from recycling-oriented pathways towards reuse requires anticipating material availability in relation to specific end-use applications, as highlighted by Arora et al. (2020), which further constrains its feasibility. By contrast, reuse considerations differ for floor slabs. As these elements remain in place, their reuse does not necessarily depend on anticipating a specific end-use application. However, a distinction must be made between internal and external paved areas. Floor slabs within warehouses are more susceptible to damage during operation due to interventions such as rack anchoring, internal partitions, or the addition of office areas, which can reduce their reuse potential. Paved areas in shared spaces of LCs are in general less intervened over the operational phase, which may allow for a higher degree of reuse at EOL.

Beyond recycling and component-level reuse, other circular strategies may also be relevant for logistics buildings, particularly those retaining a substantial share of the existing structure. Approaches such as repurposing can significantly reduce material outflows by extending the service life of buildings beyond the original function. For example, Gursel et al. (2023) assess the conversion of warehouses and other NRBs into residential apartments, showing that retaining the either the structure alone or the structure together with the façade can substantially reduce material demand, energy use, and associated emissions compared to new construction. The authors also highlight that the feasibility of such conversions is case dependent and constrained by building-specific characteristics.

Despite their potential, repurposing strategies for LCs must also account for local regulatory and planning frameworks. In practice, alternative uses must first comply with land-use regulations, given that LCs are currently located in industrial zones, and subsequently meet the building requirements associated with the new use.

Auxiliary structures within LCs, such as office buildings, light industrial sheds, or informal extensions, were not included in the analysis. These elements represent a minor share of the built area and show limited standardisation in design and construction, which prevents the definition of reliable MI factors. Their inclusion would increase the diversity of materials but is not expected to substantially alter the overall magnitude, timing, or aggregated material composition of the estimated stocks and outflows. Their relevance is therefore mainly operational. While stand-alone buildings inside LCs are unlikely to affect recovery strategies, embedded or structures attached to warehouses may complicate material separation, increasing recovery effort rather than recoverable volumes.

The spatial characteristics of the mapped centres create conditions that may facilitate large-scale recovery operations. As LCs are owned and managed by a single company, EOL decisions are more likely to be taken at the asset level rather than at the individual building level, which can simplify coordination and recovery strategies. Whether warehouses materials are recovered for reuse or recycled at other sites, or retained through on-site reuse, the concentration of MS at single locations supports more efficient recovery actions than dispersed across small-volume sites. In addition, the spatial clustering of stocks in LCs reduces transport distances for subsequent material processing, representing an additional advantage for the sector, as transport costs are a critical component of C&D waste treatment systems (Coelho & De Brito, 2013; Zhu, 2014).

In addition, spatial differences in the magnitude of mapped stocks suggest implications for operational and resource efficiency when prioritising recovery locations. Larger centres or clusters of centres, such as those located in the western and north-western submarkets, may therefore offer more favourable conditions for recovery operations than smaller or less concentrated areas. Similar spatial patterns have been observed in other studies, where higher stock densities are associated with improved material extraction efficiencies (Cheng et al., 2018). However, integrated material management strategies need to account for the differences between municipalities and their local ordinances, due to the lack of a common standard for C&D waste management (Fundación Chile, 2020).

Finally, given the predominant location of LCs within industrial zones, social disruptions associated with larger-scale operations may be reduced, whether involving material removal or on-site repurposing. While not a technical barrier, such aspects remain relevant when comparing recovery alternatives.

4.3 Validity

Internal validity

First, methodological consistency in addressing the research questions is supported by the use of a spatially explicit MSA in combination with a flow-driven MFA. The quantified material stocks, derived from building typologies and MI factors, are used directly as inputs for the flow modelling. This research design ensures coherence between stock characterisation and future outflow estimation.

Second, internal validity is strengthened by the use of primary data at the building-level in the stock quantification. MI, typology definitions, and spatial attributes were developed through site visits, visual inspection, publicly available documentation, and collaboration with industry stakeholders. Secondary data were used only where building-specific information was unavailable.

Despite relying on the best available data sources, there are differences between the MI values derived in this study and those reported in the literature. These differences can be partly explained by variations in functional aggregation as highlighted by Schebek et al. (2017). For example, Ortlepp and Deilmann (2015) analyse “storage buildings” jointly with trade-related uses, resulting in a broader range of materials, which suggests the presence of mixed combined uses beyond goods storage alone. In this respect, the warehouses analysed here more closely resemble “agricultural commercial buildings” in terms of functional use, although differences of around 30% still exist relative to the average MI factor adopted in this study. In addition, the use of typologies necessarily implies simplifications, and variations in material use and construction styles within the sector are not fully captured. Construction choices may further influence MI values; for instance, relatively small variations in floor slab thickness can lead to noticeable changes in material quantities, which may be further amplified when additional reinforcement is required. Together, these factors contribute to variability in MI values within otherwise comparable building categories.

In addition, uncertainty regarding warehouse service life limits the precision of future material outflows. Therefore, a sensitivity analysis is used to show how this uncertainty affects the results and the overall relevance of this parameter for the temporal distribution of material outflows. The lifespan used, while aligned with locally available information and international studies (Andersen & Negendahl, 2023), is not specific to logistics buildings. Internal validity is therefore maintained by explicitly treating this parameter as uncertain and by interpreting related results accordingly.

Finally, transparency and reproducibility are supported through systematic documentation of data sources, assumptions, and modelling steps. Input datasets, intermediate results, and scripts are organised and provided as SM, enabling traceability of the analysis. This aligns with the FAIR data principles, facilitating verification and reuse of the work.

External validity

Regarding building typologies and the associated MI factors, these are expected to exhibit a degree of external validity beyond the Metropolitan Region. This is due to the high level of standardisation in logistics building design and construction, as well as the presence of common industry actors operating across Chile and, in some cases, other Latin American countries. Under conditions where structural systems and design standards do not differ substantially, the defined typologies and MI factors may be transferable. For instance, this applies to privately owned warehouses, such as those developed by retail companies, which typically share similar characteristics. Even where internal or functional differences exist, the MI factors may still be applied as a baseline when the main structural system is comparable.

By contrast, the external validity of parameters used to model future material availability, particularly building service life assumptions, is more limited in terms of transferability. In Chile, service lives of buildings are not systematically recorded and, as stressed by

Augiseau and Barles (2017), stock removal processes depend on technical, social, economic, and political factors, which may vary across regions. As a result, while the lifetime assumptions adopted in this study are appropriate for exploratory analysis of future material availability in the sector, they should not be directly extrapolated to other contexts without careful consideration of local conditions.

Beyond parameter transferability, several of the main findings of this study are expected to hold in other logistics-related contexts with similar development patterns. These include the spatial concentration of stocks, the existence of limited and standardised typologies, the dominance of concrete, and the temporal mismatch between rapid stock accumulation and future material availability. However, the magnitude and temporal dynamics depend on local conditions and should be interpreted accordingly.

4.4 Limitations

This section discusses the limitations related to the scope, resources, data availability, and modelling choices of the study.

Scope

Within the scope of this study, the analysis focuses on MS existing in 2024 and their future availability under and EOL perspective. As a result, material flows from the operational phase during the service life of LCs are not considered. Future material availability is represented as the removal of materials from the logistics building stock, without distinguishing between physical demolition and changes in use. In addition, the study quantifies material availability but does not assess recovery efficiencies or downstream material use pathways, as these depend on technical, regulatory, and market conditions that fall outside the scope of the analysis. Consequently, the estimated UM potential represents a theoretical upper bound rather than an estimate of recoverable material flows. These limitations do not affect the quantified stock or outflow results, but they limit the extent to which these results can inform definitive decisions about subsequent processes.

The analysis focuses on large LCs centres in the Santiago Metropolitan Area (approximately those exceeding 30,000 m^2 of built area). As such, the quantified stocks provide a representative baseline of warehouse infrastructure in the region, which could be further refined as additional data become available.

In addition, this study does not examine the underlying drivers of material choice in warehouse construction. Although the analysed buildings provide comparable service units (e.g. floor area or clear height), differences in material use may also be influenced by architectural, economic, or performance-related considerations (such as fire resistance), which are not addressed in the present analysis.

Methods

Within the applied methods, the bottom-up MSA approach relies on archetypes to represent warehouse construction, assuming common characteristics across buildings that are translated into MI factors. As a result, variability in material use across individual buildings may not be fully captured. In turn, the flow-driven MFA estimates future material outflows based on historical construction inflows and assumed service lifetimes, without considering other external drivers. Accordingly, projected outflows should be interpreted as an exploratory representation of material availability conditional on the existing stock, rather than as forecasts of future construction or demolition activity.

Data availability

Limitations in data availability affected several aspects of the analysis. Publicly available information on total material use in the Chilean construction sector is scarce and largely aggregated. Indicators reported by institutions such as the Chilean Chamber of Construction (Cámara Chilena de la Construcción, n.d.) do not provide even aggregated data on material use by the construction sector. Similarly, national statistics such as cement dispatch data reported by the Chilean Central Bank (Banco Central de Chile, n.d.) capture only a single input within concrete production and may correspond to multiple end uses. As a result, available sources are not directly comparable with the estimates developed in this study, limiting the benchmarking and validation of the quantified stocks.

At the building level, several attributes had to be reconstructed due to data limitations. As no public MI factors dataset exist in the Chilean context, adapted blueprints were used to develop MI factors for the sector, which may limit their specificity to actual construction practices. In addition, building footprint data were obtained from non-official sources and refined through manual digitisation and data harmonisation, introducing potential uncertainty in area estimates used as inputs for the MSA. Regarding building heights, as there are no accessible records, the classification of buildings into categories relied on visual inspection using publicly available imagery and on-site verification. This approach is labour-intensive, limiting the scalability of the chosen method to a broader spatial scope, while potentially introducing additional uncertainty. Construction years for most warehouses were reconstructed from satellite imagery rather than official records, which in many cases do not exist or are not accessible at the building level. Finally, the extraction of building-level attributes from cadastral datasets was challenging, as SII data are organised at the cadastral block level and often group multiple warehouses under a single identifier, preventing the direct assignment of attributes.

Finally, limitations in service life data poses a major constraint for modelling future material availability. No logistics-specific and systematically recorded lifetime data exist in Chile, requiring the use of residential sector data as a proxy for warehouse buildings. As discussed previously, this parameter is key for the sector's dynamics; consequently, MFA results should be interpreted as exploratory and conditional.

4.5 Recommendations

This section outlines recommendations with a focus on improving data availability, institutional coordination, and the use of stock-based information to support anticipatory material management.

Data availability

To improve the flow of building data between public institutions, stronger coordination and data exchange between agencies such as Municipal Building Authority (DOM), National Statistics Institute (INE), and SII are needed to enable the consistent identification of buildings by sector, C&D dates, uses, and physical characteristics. In the case of SII, cadastral records should be georeferenced at the individual building level rather than aggregated at the cadastral block level.

Improved data quality requires more standardised and detailed reporting of structural systems, floor areas, uses, C&D dates, and construction materials in building permit applications, for both residential and non-residential developments. In addition, building permits managed by municipal authorities (DOM) could include disaggregated information on material use by type and quantity. At the statistical level (INE), a revision of construction use classification codes is also needed, as warehouses could be classified under two categories 800 (Other: workshops, sheds, garages) or 801 (Transport and storage), which substantially reduces data resolution and increases uncertainty in stock-based material analyses. To further improve MS quantification of LCs, refined typologies could be derived from sector-specific blueprints and projects to better represent the sector's main characteristics. These typologies could also incorporate additional buildings components as well as building services, such as mechanical, electrical, and plumbing (MEP) installations. This would support more standardised future research while enhancing the resolution of the MI factors, improving MS assessment of the sector.

Finally, to enhance data availability and accessibility, the development of an open-access, unified, and georeferenced building-level database to support stock-based planning and research is recommended. This platform could incorporate reference libraries of building typologies and MI factors by sector to facilitate future assessments.

Integrating stock-based material information into planning processes

Beyond the current focus on reducing and diverting waste streams from landfills during construction, existing CE initiatives in the construction sector that aim to link material availability with demand primarily rely on the exchange of materials from ongoing projects or demolition activities (e.g. Red Circular Araucanía). These initiatives follow a reactive logic, rather than relying on anticipated knowledge of materials embedded in existing buildings. This highlights an opportunity for future platforms in which detailed building-level material information can be used to anticipate and match future material availability with potential demand, moving beyond reactive waste handling towards planned material flow management.

In this context, policy roadmaps and strategies in Chile increasingly emphasise expanding recovery capacity and reducing the disposal of C&D waste. However, questions remain as to how future objectives and targets are defined in the absence of quantitative information on the timing, location, and composition of material releases from the existing building stock. This may limit the alignment between capacity development, policy targets, and future material availability.

In this sense, the integration of spatially explicit MSA–MFA into planning processes, from sectoral to national levels, is recommended to support the definition of recovery objectives and capacity needs based on anticipated material releases from the existing building stock, rather than on ex post, aggregated national-level indicators. This would enable more anticipatory and context-specific strategies for material management across scales.

5 Conclusions

This thesis assesses the urban mining potential of logistics centres in Santiago, Chile, by examining where MS are located, how the sector is characterised, the magnitude and composition of these stocks, and when they are expected to become available as buildings reach the end of their service life.

As of 2024, the total MS embedded in the mapped LCs amounts to approximately 5.2 million tonnes, of which around three quarters are contained within buildings and the rest in shared paved areas. The material composition of warehouse buildings is highly concentrated, with concrete overwhelmingly dominating the stock, accounting for over 92% of the total mass. Steel represents approximately 5%, while masonry accounts for less than 3%. These stocks are spatially concentrated along major highways in the outer areas of Santiago and are unevenly distributed across the Metropolitan Region, with a large share located in only a limited number of municipalities, predominantly in the western and north-western areas of the city. Given the relatively recent expansion of the sector and the service life assumptions adopted, most materials will remain embedded in the building stock for several decades, with material availability expected to peak towards the second half of the 21st century.

Taken together, the results indicate that LCs in Santiago represent a large but predominantly long-term UM potential. MS are spatially concentrated across the city, with a substantial share embedded in a limited number of especially large, concrete-dominated centres.

This study contributes to the field of Industrial Ecology by producing new empirical evidence on the spatial distribution, composition, and temporal dynamics of MS embedded in LCs, strengthening the understanding of NRBs, a sector that remains largely understudied. It delivers the first sector-specific MS inventory of LCs in Chile, contributing evidence from Latin America, a region that remains underrepresented in MS research. Methodologically, the study demonstrates how bottom-up MSA and dynamic MFA can be combined under data-scarce conditions, providing a transparent and reproducible workflow that can be adapted to other NRB sectors and urban contexts. By characterising how materials are distributed within the BE and introducing a temporal dimension linking existing stocks to future outflows, the study provides anticipatory knowledge on when, where, and in which material form releases are likely to occur. This supports the recognition of buildings as long-term material reservoirs and informs future efforts to reduce environmental pressures associated with primary material extraction and waste disposal.

The results provide a basis for future analyses related to the construction sector and urban metabolism studies. MS and flow estimates developed can be used as input data in environmental assessments, support economic analyses for material recovery strategies, and inform policy-oriented discussion aimed to reduce material throughput. In addition, the methodological approach can be replicated in other sectors, including residential and NRBs, to improve the overall understanding of urban MS.

Given the findings and limitations of this thesis, future research should focus on:

- Assessing how existing life-extension and EOL alternatives beyond landfill align with projected material availability for retention rather than dissipation.

- Complementarily, examining how external factors influence the adoption of these alternatives, recognising that enablers or barriers do not necessarily ensure improved material use efficiency.
- Scaling the scope of sector's assessment, given potential transferability of MI factors, to obtain national level estimates.
- Assessing the regulatory landscape for material substitution, particularly how Chilean standards, mainly for concrete, influence the effective use of secondary materials.
- Exploring the link between MS and service provision in the logistics sector, while carefully defining functional boundaries given the regional and inter-regional role of LCs.
- Extending MS analyses to additional sectors to build a more comprehensive picture of urban stocks beyond logistics infrastructure.
- Examining data availability as a structural constraint, assessing how it shapes the volume, scope, and uncertainty of MS assessments in Chile.

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Declarations

For transparency purposes the following statements are declared:

1. To ensure transparency and avoid any potential conflict of interest, the author declares a minority ownership in one of the companies included in the study. Nevertheless, data collection, processing, analysis, and presentation were conducted objectively and following the supervisors' guidance. All information supporting the findings of this research is provided in the main text, the appendices, or the SM.

2. ChatGPT, as a generative artificial intelligence tool, was used to check grammar and improve language clarity and flow. The tool was not used to generate data or results. Additionally, it was used as assistance for reviewing Python scripts for logic and potential errors. All scripts were developed and executed by the author. The research design, together with data processing and analysis was completely done by the author. During QGIS data analysis and processing, ChatGPT was used to support the efficient use of specific in-program tools. Continuous checks were carried out to ensure validity throughout the process. Example of prompts used:
   a. *"For the following paragraph, could you check the flow and provide feedback for possible adjustments to improve clarity?"*
   b. *"Based on the following sentence, is there any error regarding coherence or use of English if I want to say...?"*
   c. *"Is this sentences too long or difficult to understand in English?"*
   d. *"I got this error... when running this script cell..., what might be the problem according to the message?"*
   e. *"I need to merge data from the attribute table from different layers, what are the best tools in QGIS to do this?"*
   f. *"In the map layout section of QGIS, is there a way to add... to the existing map?"*

Supplementary Materials

The SM are provided in digital form at the following link. An overview of all the documents is presented in ***Table 9***. File names correspond to those used in the workflow diagrams shown in **Appendix A.1** and **B.2**. SM link: https://github.com/rodrigosalva1988/Thesis_MScIE_RSA

Within the SM, each calculation spreadsheet includes a "File overview" sheet explaining the purpose of the file and the content of each worksheet. In addition, a simple coding system is used to provide explanations and to locate the original tables and figures used in this document. The following examples show the colour code used:

Explanation: *** Extracted from "RM_WH_main.xlsx", sheet "Yearly_MS_analysis", cells "P1:Z49"**

Link: *** In Thesis: Table 5. Expected material outflow per decade using a fixed 60-year lifetime, in tonnes (t).**

Table 9. List of the supplementary materials provided, including file names, formats, and corresponding thesis sections.

Section	SM code	File name	File extension	File type
2.1 MSA	1.1	Main_actors.xlsx	.xlsx	Excel spreadsheet
	1.2	Companies_locations.kmz	.kmz	Kmz geographic data file
	1.3	File_proccessing_logbook.xlsx	.xlsx	Excel spreadsheet
	1.4	SII_data_extraction_v2.py	.py	Python script
	1.5	filtered_SII_municipalities_blocks_v2.xlsx	.xlsx	Excel spreadsheet
	1.6	Logistics Centres visual documentation – Part 1	.pdf	PDF file
	1.7	Logistics Centres visual documentation – Part 2	.pdf	PDF file
	1.8	Material_intensities.xlsx	.xlsx	Excel spreadsheet
	1.9	MI_for_QGIS.csv	.csv	Csv file with MI
	1.10	RM_WH_main.xlsx	.xlsx	Excel spreadsheet
2.2 dMFA	2.1	Configuration 0.xlsx	.xlsx	Excel spreadsheet
	2.2	Configuration 1.xlsx	.xlsx	Excel spreadsheet
	2.3	Configuration 2.xlsx	.xlsx	Excel spreadsheet
	2.4	Configuration1_inflows.xlsx	.xlsx	Excel spreadsheet
	2.5	Configuration2_inflows.xlsx	.xlsx	Excel spreadsheet
	2.6	Configuration1_inflows.csv	.csv	Csv file with inflow data
	2.7	Configuration2_inflows.csv	.csv	Csv file with inflow data
	2.8	dMFA_outflows_c1.py	.py	Python script
	2.9	dMFA_outflows_c2.py	.py	Python script
	2.10	outflows_configuration1.xlsx	.xlsx	Excel spreadsheet
	2.11	outflows_configuration1_by_cohort.xlsx	.xlsx	Excel spreadsheet
	2.12	pdf_comparison_selected_cohorts.xlsx	.xlsx	Excel spreadsheet
	2.13	outflows_configuration2.xlsx	.xlsx	Excel spreadsheet
	2.14	outflows_configuration2_by_cohort.xlsx	.xlsx	Excel spreadsheet
	2.15	dMFA_sensitivity_c1.py	.py	Python script
	2.16	outflows_configuration1_mean_minus15.xlsx	.xlsx	Excel spreadsheet
	2.17	outflows_configuration1_mean_minus30.xlsx	.xlsx	Excel spreadsheet
	2.18	outflows_configuration1_mean_plus15.xlsx	.xlsx	Excel spreadsheet
	2.19	outflows_configuration1_mean_plus30.xlsx	.xlsx	Excel spreadsheet
	2.20	Outflows_all_configurations.xlsx	.xlsx	Excel spreadsheet
Supporting files	3.1	RM_logistic_centres.gpkg	.gpkg	GIS-geopackage file
	3.2	RM_WH.gpkg	.gpkg	GIS-geopackage file
	3.3	RM_WH_BaseScenario.gpkg	.gpkg	GIS-geopackage file
	3.4	RM_LC_PA_final2.gpkg	.gpkg	GIS-geopackage file
	3.5	RM_LC_OA_final2.gpkg	.gpkg	GIS-geopackage file
	3.6	RM_Municipalities_for_future_outflows.gpkg	.gpkg	GIS-geopackage file
	3.7	environment.yml	.yml	YAML environment

Appendices

This section includes complementary material such as workflow diagrams, explanations, justifications, large tables, detailed calculations, and extended figures or diagrams that support the main text. Tables and figures are numbered separately from those in the main document, using the prefixes A, B, and C according to the appendix section.

Appendix A – Material Stock Accounting

A.1. Data integration and processing workflow for Material Stock Accounting

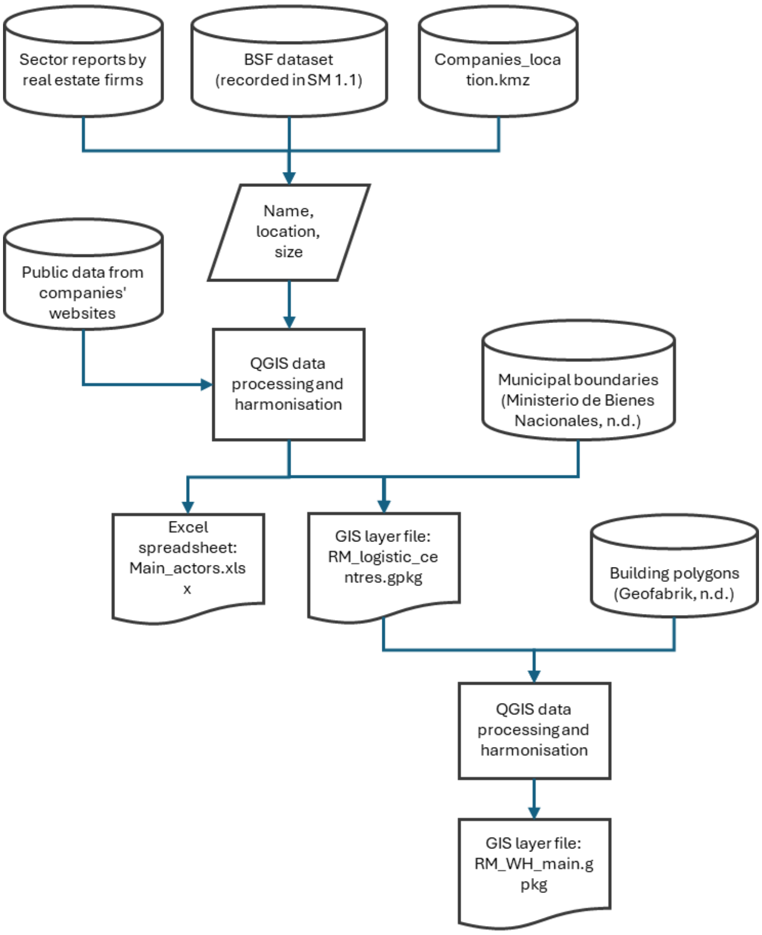

Figure A. 1. Processing workflow indicating the main steps, data sources, and output files used for GIS data integration and development.

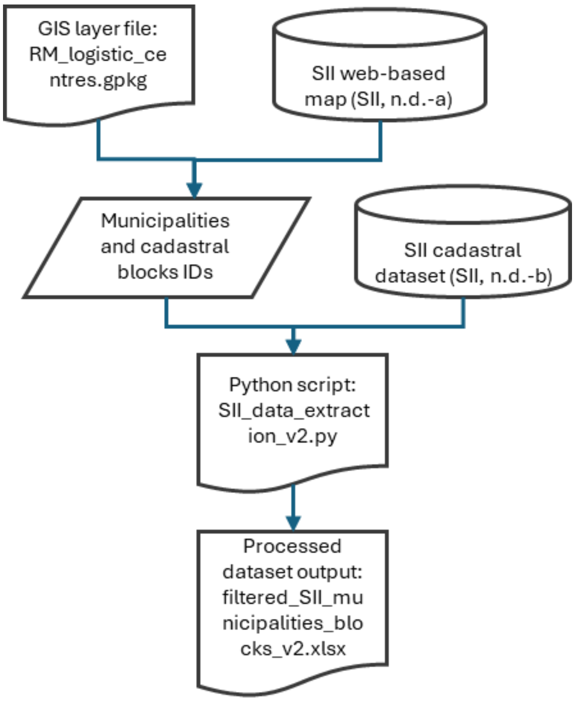

Figure A. 2. Processing workflow indicating the main steps, data sources, and output files used for SII cadastral data analysis.

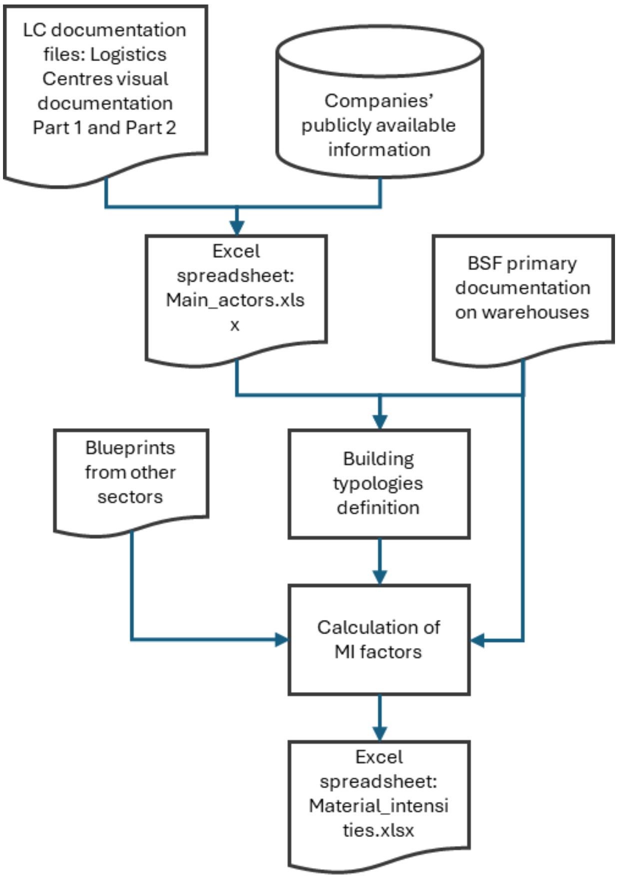

Figure A. 3. Processing workflow indicating the main steps, data sources, and output files used for building typologies definition and MI development.

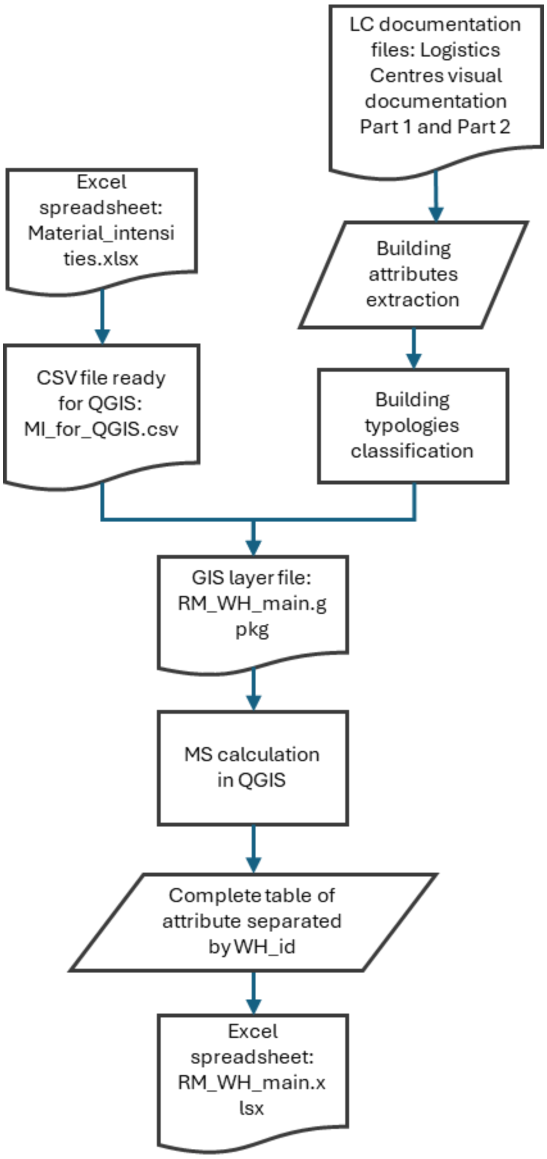

Figure A. 4. Processing workflow indicating the main steps, data sources, and output files used for building typology classification and MS calculation.

A.2. Data sources for building typology development

Table A. 1. Online sources consulted for the identification of construction characteristics of logistics centres.

Company	Online sources
Anya	https://anya.cl/nuestros-centros/
Centro de Bodegaje Puerta Sur	No public information available
Bodegas San Francisco	https://bsf.cl/
Bodegas San Martin	https://bodegasanmartin.cl/
Chilena	https://assetcbre.cl/index.php/properties/cd-lo-boza-2/;
Consolidada-Zurich	https://industrial.patio.cl/details/40-patio-miraflores
Campos de Chile	https://www.avanzapark.cl/bodegas-arriendo/condominio-arriendo-la-divisa; https://www.avanzapark.cl/bodegas-arriendo/condominio-arriendo-san-bernardo; https://www.loginsa.com/?page_id=36
Central Bodegas	https://centralbodegas.cl/centros-multi-arrendatario/milagros-de-nos/
Cimenta	https://cimenta.cl/bodegas/
Cargo Park	https://assetcbre.cl/wp-content/uploads/Brochure-Cargo-Park.pdf
Danco	https://www.danco.cl/centros/; https://centralbodegas.cl/centros-multi-arrendatario/lo-boza/
DLS	https://bodepark.cl/; https://espaciobodegas.cl/arriendo-bodegas-logisticas-pudahuel/
Bodegas F.A.C	https://www.bodegasfac.cl/caupolican
Bodenor Flexcenter	https://bodenorflexcenter.cl/parques-logisticos/
Global Storage	https://www.globalstorage.cl/arriendo-de-bodegas-centro-logistico-globalstorage/
Imolog	https://www.imolog.cl/centro-logistico/
Inarco	https://inarco.cl/project/centro-de-distribucion-la-polar/
Invac	https://invac.cl/red-de-bodegas/
Megacentro	https://www.megacentro.com/centros/
Megaflex	https://www.isj.cl/megaflex
Mersan	https://mersan.cl/bodegas/
Inmobiliaria E Inversiones Mingjia Limitada	No public information available
OPL	https://www.opl.cl/opl-enea-i; https://www.opl.cl/opl-laguna-sur
Bodegas Premier	https://www.bodegaspremier.cl/centro-lo-boza; https://www.bodegaspremier.cl/centro-san-bernardo
Workcenter	https://work-center.cl/work-center-miraflores/; https://work-center.cl/work-center-vespucio/

* *Note: Multiple URLs in a row refer to different logistics centres operated by the same company.*

Table A. 2. Publicly available information retrieved from company websites and online sources used to support the identification of building typologies.

Company	LC	Type of information source	Eave height information (m)	Other comments
Anya	Colo Colo; Lo Boza; Lo Echevers; Lo Echevers 400; Miraflores	Company website	Not specified	Visual inspection suggests concrete wall systems
Centro de Bodegaje Puerta Sur	Centro Puerta Sur	No public information available	Not specified	No publicly available information on construction characteristics was identified
Bodegas San Francisco	Huingan; La Farfana; Laguna Sur; Lo Aguirre; Lo Echevers; Lo Espejo; Los Mares; Puerto Madero; Vespucio	Primary data (BSF)	6.5; 8; 9.7; 2.7 (self-storage)	Confined masonry warehouses; steel structures for self-storage units
Bodegas San Martin	Noviciados; Quilicura	Company website	Not specified	Visual inspection suggests a steel structural system with metal cladding
Chilena Consolidada-Zurich	Lo Boza Lascar; Logicentro Miraflores; Logicentro SPF	Real estate listing; Project brochure	10	Height information (10 m) reported for Lo Boza only
Campos de Chile	Enea 1; La Divisa; Loginsa; San Bernardo	Company website	8.5–11; 9; 10	Height information available for La Divisa (8.5–11 m) and San Bernardo (9–10 m) only; no information for CDC/Loginsa. Visual inspection suggests steel structures, with concrete walls in front office areas
Central Bodegas	Casas Viejas; La Vara; Nos	Company website; Blueprints	8.1; 6.7	Confined masonry structures. Exact heights and construction specifications available from blueprints for Nos (8.1 m) and La Vara (6.7 m); Casas Viejas presents similar characteristics to La Vara.
Cimenta	Gral Velasquez; Lascar; Licancabur	Company website	8; 10.5; 9.3	Height information reported for Gral. Velásquez (8 m), Lo Boza I (10.5 m) and Lo Boza II (9.3 m); no additional information on construction systems was identified
Cargo Park	Quilicura 1; Quilicura 2	Project brochure (PDF)	8	Height information (8 m) reported for Quilicura I and II; visual inspection suggests steel–concrete structural systems
Danco	Lo Boza; Miraflores	Company website; Project brochure	11+	Height information (11+ m) reported for Lo Boza and Miraflores. For Lo Boza, the available brochure corresponds to a different project; for Miraflores, no information on construction materials was identified
DLS	Bodepark; Centro de Bodegaje Pudahuel	Company website	7–9; 10	Height information reported for Bodepark LC (7–9 m) and Centro Pudahuel (10 m). Visual inspection suggests concrete pillars for Bodepark LC; no information on construction materials was identified for Centro Pudahuel
Bodegas F.A.C	Caupolican	Company website	6	Warehouses made of reinforced concrete

Table A. 2 (continued).

Bodenor Flexcenter	ENEA 1; ENEA 2; Lo Boza 120; Lo Boza 422; Lo Boza 441; Puerto Vespucio	Company website	9.5; 11	Height information reported for Enea I and II (9.5 m) and for Lo Boza 120, 422 and 441 (11 m); no publicly available information on construction materials was identified
Global Storage	Lo Espejo	Company website	12	Concrete structural system with concrete pillars and concrete floor slab (HF 4.3, 16 cm thick)
Imolog	Imolog	Company website	Not specified	No publicly available information on construction characteristics was identified
Inarco	Pto Stgo	Company website	Not specified	No publicly available information on construction characteristics was identified
Invac	El Cerro	Company website	9	Reinforced concrete pillars and walls
Megacentro	Aeroparque; Buenaventura; Carrascal; Cordillera; ENEA; Miraflores; Miraflores III; Noviciado; San Bernardo	Company website	Not specified	No publicly available information on construction characteristics was identified
Megaflex	Colina	Company website	Not specified	No publicly available information on construction characteristics was identified
Mersan	Lo Espejo	Company website	Not specified	Precast concrete structure with concrete panel cladding; roofs include translucent panels
Inmobiliaria E Inversiones Mingjia Limitada	Lo Espejo	No public information available	Not specified	No publicly available information on construction characteristics was identified
OPL	ENEA 1; Laguna Sur	Company website	11; 9–10	Height information available (11 m and 9–10 m); no information on construction materials was identified
Bodegas Premier	Lo Boza; San Bernardo	Company website	8	Visual inspection suggests confined masonry structures
Workcenter	Workcenter Miraflores; Workcenter Vespucio	Company website	Not specified	No publicly available information on construction characteristics was identified

A.3. Logistics sector context and submarkets

Over the past four decades, logistics centres in Santiago have undergone significant transformation. They have expanded in scale and gradually pushed towards the outskirts of the city, often occupying industrial zones or areas formerly used for agriculture. At the same time, the number of companies has increased, ranging from small self-storage complexes to large logistics hubs strategically located to optimise transport and strengthen local supply chains.

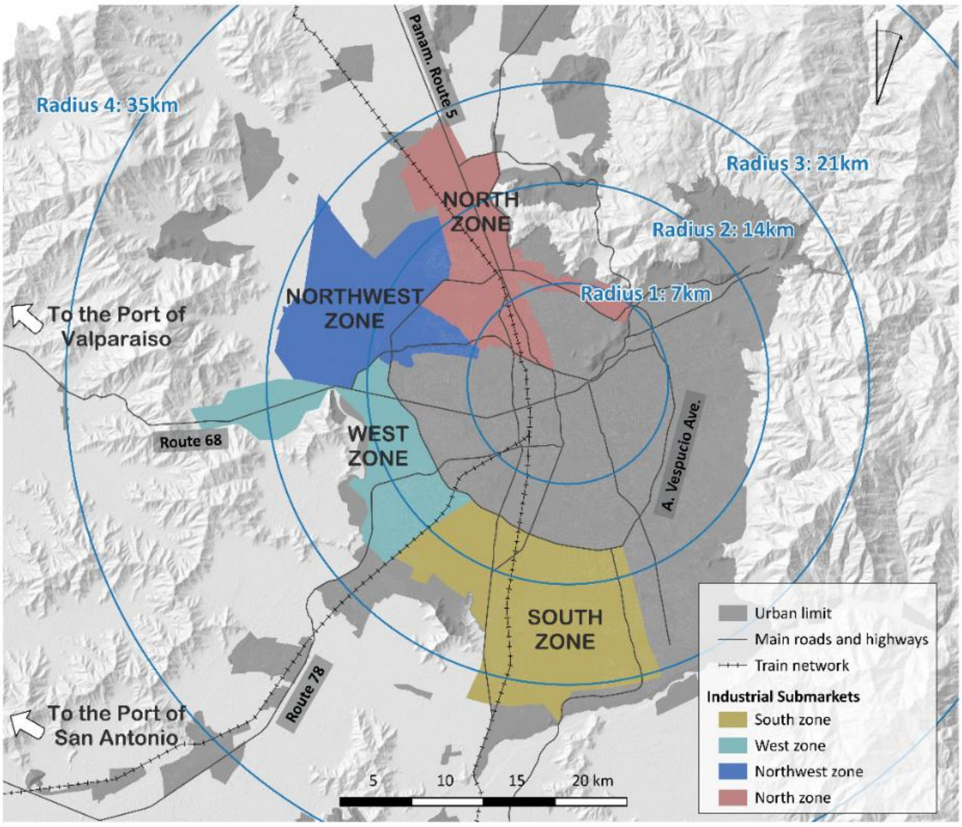

Figure A. 5. Industrial submarkets and logistics zones in Santiago Metropolitan Area (own illustration, adapted from (Cushman & Wakefield, 2025)).

Santiago, being in Chile's central valley, has no direct maritime access and therefore relies on the Ports of San Antonio and Valparaíso as its main gateways for goods. Overland connection with the rest of the country is made through Pan-American Route 5 and the train network. ***Figure A. 5*** show the four main industrial submarkets, which are strategically located to ensure efficient access both to the ports and the city itself through the main urban highway network. These submarkets are primarily located between 7 and 21 km from the city centre. The official urban boundary (in grey in the figure) extends well beyond the Américo Vespucio ring road, which has historically been regarded as the city's effective limit. Industrial and logistics developments have therefore tended to expand outward beyond this boundary, although some activity still remains within it.

Sector trends and warehouse classifications

Regarding sector dynamics, during the second half of 2024, nearly 80,000 m^2 of warehouses were developed, mainly in the northern and western areas of Santiago. Vacancy rates have remained below 10% over the past decade, closing 2024 at 5.7%

(Colliers, 2025). In the first semester of 2025 alone, 260,000 m^2 of warehouses were built (CBRE, 2025). Furthermore, an additional 220,000 to 260,000 m^2 are expected to be built during 2025 (CBRE, 2025; Cushman & Wakefield, 2025).

Different classifications of warehouse types are used in the sector. In general, Class A warehouses are typically less than 15 years old, located near main roads or industrial parks, and feature higher clear heights (from around 10 metres), with a minimum floor area of approximately 2,500 m^2. By contrast, Class B warehouses are generally older (over 15 years), located on secondary roads, with lower clear heights (around 8 metres), smaller floor areas, and more limited infrastructure, though they still provide functional space for logistics operations (Colliers, 2025). However useful for commercial purposes, these classifications are not directly relevant to the objectives of this study. Thus, both classes are included without distinction beyond their assigned typology since their separation is often ambiguous, they account for significant shares of total floor area and are frequently present within the same LC.

A.4. Supporting tables of mapped logistics centres

Table A. 3. Companies name and code.

Company	Code
Anya	ANY
Centro de Bodegaje Puerta Sur	BPS
Bodegas San Francisco	BSF
Bodegas San Martin	BSM
Chilena Consolidada-Zurich	CCZ
Campos de Chile	CDC
Central Bodegas	CEN
Cimenta	CIM
Cargo Park	CPA
Danco	DAN
DLS	DLS
Bodegas F.A.C	FAC
Bodenor Flexcenter	FLE
Global Storage	GLS
Imolog	IMO
Inarco	INA
Invac	INV
Megacentro	MEC
Megaflex	MEF
Mersan	MER
Inmobiliaria E Inversiones Mingjia Ltda	MIN
OPL	OPL
Bodegas Premier	PRE
Workcenter	WOR

Table A. 4. Distribution of logistics centres by municipality.

Municipalities	Number of centres	Share (%)
CERRO NAVIA	1	1.5%
COLINA	2	3.1%
LAMPA	2	3.1%
LO ESPEJO	1	1.5%
MAIPÚ	2	3.1%
PUDAHUEL	28	43.1%
QUILICURA	12	18.5%
RENCA	7	10.8%
SAN BERNARDO	10	15.4%
9	**65**	**100%**

Table A. 5. Land use distribution per company (m^2).

Company	Built area (m2)	Paved area (m2)	Open area (m2)	Total area (m2)	Share (%)
ANY	269,972	155,539	25,484	450,995	4%
BPS	119,625	70,409	95,309	285,343	3%
BSF	1,673,524	1,018,179	1,306,332	3,998,035	35%
BSM	80,751	56,031	25,379	162,161	1%
CCZ	88,233	61,445	9,516	159,194	1%
CDC	340,380	210,074	28,883	579,337	5%
CEN	113,344	95,041	10,004	218,389	2%
CIM	153,873	111,262	19,153	284,288	3%
CPA	72,471	62,347	15,484	150,302	1%
DAN	102,317	67,566	2,843	172,726	2%
DLS	129,682	106,727	22,437	258,846	2%
FAC	41,654	27,321	1,830	70,805	1%
FLE	609,466	366,856	94,944	1,071,266	9%
GLS	96,778	51,466	86,387	234,631	2%
IMO	29,749	24,270	48,958	102,977	1%
INA	43,848	37,311	65,600	146,759	1%
INV	46,211	31,098	11,927	89,236	1%
MEC	905,902	867,208	255,333	2,028,443	18%
MEF	33,124	24,062	6,722	63,908	1%
MER	117,956	155,209	64,223	337,388	3%
MIN	36,317	12,432	7,025	55,774	0%
OPL	104,425	72,607	9,910	186,942	2%
PRE	73,969	59,706	7,544	141,219	1%
WOR	66,539	51,080	3,069	120,688	1%
Total	**5,350,110**	**3,795,246**	**2,224,296**	**11,369,652**	**100%**

Table A. 6. Land use distribution per logistics centre (m^2).

LC	Built area (m2)	Paved area (m2)	Open area (m2)	Total area (m2)
ANY_Colo Colo	33,466	21,072	1,811	56,349
ANY_Lo Boza	65,970	41,643	1,383	108,996
ANY_Lo Echevers	72,071	38,290	11,268	121,629
ANY_Lo Echevers 400	37,653	19,948	5,806	63,407
ANY_Miraflores	60,812	34,586	5,216	100,614
BPS_Puerta Sur	119,625	70,409	95,309	285,343
BSF_Huingan	30,296	25,826	5,938	62,060
BSF_La Farfana	396,178	326,302	391,131	1,113,611
BSF_Laguna Sur	218,497	109,128	5,042	332,667
BSF_Lo Aguirre	173,765	112,073	826,846	1,112,684
BSF_Lo Echevers	111,382	55,602	4,297	171,281
BSF_Lo Espejo	88,141	46,010	4,594	138,745
BSF_Los Mares	42,939	28,550	23,477	94,966
BSF_Puerto Madero	430,188	244,367	32,551	707,106
BSF_Vespucio	182,138	70,321	12,456	264,915
BSM_Noviciados	26,509	18,944	23,330	68,783
BSM_Quilicura	54,242	37,087	2,049	93,378
CCZ_Lo Boza Lascar	33,208	18,852	1,756	53,816
CCZ_Logicentro Miraf	31,189	17,528	2,544	51,261
CCZ_Logicentro SPF	23,836	25,065	5,216	54,117
CDC_Enea 1	168,852	98,660	8,559	276,071
CDC_La Divisa	35,530	24,168	-	59,698
CDC_Loginsa	28,340	12,171	1,642	42,153
CDC_San Bernardo	107,658	75,075	18,682	201,415
CEN_Casas Viejas	34,796	24,488	4,328	63,612
CEN_La Vara	41,970	38,938	5,676	86,584
CEN_Nos	36,578	31,615	-	68,193
CIM_Gral Velasquez	57,987	27,841	13,128	98,956
CIM_Lascar	32,645	23,748	1,943	58,336
CIM_Licancabur	63,241	59,673	4,082	126,996
CPA_Quilicura 1	45,667	48,081	8,510	102,258
CPA_Quilicura 2	26,804	14,266	6,974	48,044
DAN_Lo Boza	43,342	30,430	709	74,481
DAN_Miraflores	58,975	37,136	2,134	98,245
DLS_Bodepark	43,099	38,313	878	82,290
DLS_Centro Pudahuel	86,583	68,414	21,559	176,556
FAC_Caupolican	41,654	27,321	1,830	70,805
FLE_ENEA 1	160,489	115,537	33,943	309,969
FLE_ENEA 2	189,517	99,453	34,026	322,996
FLE_Lo Boza 120	100,730	56,013	3,246	159,989
FLE_Lo Boza 422	84,209	46,759	17,449	148,417
FLE_Lo Boza 441	43,812	24,406	1,902	70,120
FLE_Puerto Vespucio	30,709	24,688	4,378	59,775
GLS_Lo Espejo	96,778	51,466	86,387	234,631
IMO_Imolog	29,749	24,270	48,958	102,977
INA_Pto Stgo	43,848	37,311	65,600	146,759
INV_El Cerro	46,211	31,098	11,927	89,236
MEC_Aeroparque	196,828	211,286	89,493	497,607
MEC_Buenaventura	307,200	249,916	73,509	630,625
MEC_Carrascal	45,953	52,137	35,423	133,513
MEC_Cordillera	86,039	64,570	7,931	158,540
MEC_ENEA	58,322	48,055	2,828	109,205
MEC_Miraflores	85,140	110,027	26,125	221,292
MEC_Miraflores III	38,621	42,867	2,403	83,891
MEC_Noviciado	37,292	34,733	8,415	80,440
MEC_San Bernardo	50,507	53,617	9,206	113,330
MEF_Colina	33,124	24,062	6,722	63,908
MER_Lo Espejo	117,956	155,209	64,223	337,388
MIN_Lo Espejo	36,317	12,432	7,025	55,774
OPL_ENEA 1	44,310	30,901	4,844	80,055
OPL_Laguna Sur	60,115	41,706	5,066	106,887
PRE_Lo Boza	45,487	32,442	1,625	79,554
PRE_San Bernardo	28,482	27,264	5,919	61,665
WOR_Workcenter Miraf	36,800	27,306	781	64,887
WOR_Workcenter Vespu	29,739	23,774	2,288	55,801
65	**5,350,110**	**3,795,246**	**2,224,296**	**11,369,652**
	47%	**33%**	**20%**	**100%**

A.5. Supporting tables for building areas and material intensities

Table A. 7. Annual inflow, total stock, and moving average of built area in logistics centres (1977–2024).

Year	Annual inflow (m2)	Total stock (m2)	Moving average of built area (m^2/year)
1977	3,535	3,535	-
1978	0	3,535	-
1979	0	3,535	-
1980	0	3,535	-
1981	0	3,535	-
1982	0	3,535	-
1983	0	3,535	-
1984	94,233	97,768	-
1985	0	97,768	-
1986	0	97,768	9,777
1987	0	97,768	9,423
1988	0	97,768	9,423
1989	0	97,768	9,423
1990	0	97,768	9,423
1991	0	97,768	9,423
1992	0	97,768	9,423
1993	12,279	110,047	10,651
1994	21,529	131,576	3,381
1995	0	131,576	3,381
1996	35,978	167,554	6,979
1997	25,999	193,553	9,579
1998	32,506	226,059	12,829
1999	87,625	313,684	21,592
2000	12,979	326,663	22,890
2001	46,231	372,894	27,513
2002	177,471	550,365	45,260
2003	72,059	622,424	51,238
2004	38,544	660,968	52,939
2005	79,617	740,585	60,901
2006	76,288	816,873	64,932
2007	160,225	977,098	78,355
2008	265,644	1,242,742	101,668
2009	18,504	1,261,246	94,756
2010	130,823	1,392,069	106,541
2011	214,264	1,606,333	123,344
2012	341,625	1,947,958	139,759
2013	293,422	2,241,380	161,896
2014	400,225	2,641,605	198,064
2015	372,982	3,014,587	227,400
2016	273,885	3,288,472	247,160
2017	197,485	3,485,957	250,886
2018	457,716	3,943,673	270,093
2019	309,767	4,253,440	299,219
2020	197,549	4,450,989	305,892
2021	178,599	4,629,588	302,326
2022	429,629	5,059,217	311,126
2023	165,234	5,224,451	298,307
2024	125,659	5,350,110	270,851

Table A. 8. Cumulative built area stock by warehouse typology (1977–2024).

Year	CW11.5	CW8	Others	MINIW2.7	MW6.5	MW8	MW9.7	SW11.5	SW8
1977	0	0	439	0	3,096	0	0	0	0
1978	0	0	439	0	3,096	0	0	0	0
1979	0	0	439	0	3,096	0	0	0	0
1980	0	0	439	0	3,096	0	0	0	0
1981	0	0	439	0	3,096	0	0	0	0
1982	0	0	439	0	3,096	0	0	0	0
1983	0	0	439	0	3,096	0	0	0	0
1984	0	0	439	2,280	3,096	0	0	15,154	76,799
1985	0	0	439	2,280	3,096	0	0	15,154	76,799
1986	0	0	439	2,280	3,096	0	0	15,154	76,799
1987	0	0	439	2,280	3,096	0	0	15,154	76,799
1988	0	0	439	2,280	3,096	0	0	15,154	76,799
1989	0	0	439	2,280	3,096	0	0	15,154	76,799
1990	0	0	439	2,280	3,096	0	0	15,154	76,799
1991	0	0	439	2,280	3,096	0	0	15,154	76,799
1992	0	0	439	2,280	3,096	0	0	15,154	76,799
1993	0	0	439	2,280	15,375	0	0	15,154	76,799
1994	0	15,007	439	3,712	20,465	0	0	15,154	76,799
1995	0	15,007	439	3,712	20,465	0	0	15,154	76,799
1996	0	45,716	439	3,712	25,734	0	0	15,154	76,799
1997	0	45,716	439	3,712	51,733	0	0	15,154	76,799
1998	0	45,716	439	3,712	81,455	0	0	15,154	79,583
1999	0	100,453	439	6,616	81,455	0	0	15,154	109,567
2000	0	100,453	439	8,388	86,501	6,161	0	15,154	109,567
2001	0	126,897	1,491	8,388	105,236	6,161	0	15,154	109,567
2002	0	126,897	1,491	14,499	198,513	84,244	0	15,154	109,567
2003	0	144,038	2,396	16,691	214,488	109,692	0	15,154	119,965
2004	0	153,895	2,396	18,820	221,789	128,949	0	15,154	119,965
2005	0	153,895	2,396	18,820	221,789	208,566	0	15,154	119,965
2006	0	170,074	2,396	18,820	221,789	268,675	0	15,154	119,965
2007	0	239,945	2,396	21,096	244,048	331,251	0	16,979	121,383
2008	0	328,869	3,297	23,733	300,217	433,202	0	16,979	136,445
2009	0	339,427	3,297	26,153	300,217	433,202	0	16,979	141,971
2010	0	359,753	3,297	27,326	312,857	516,661	0	16,979	155,196
2011	0	421,913	3,297	27,326	320,179	612,708	0	41,791	179,119
2012	52,163	442,534	3,297	31,243	361,823	741,267	0	53,968	261,663
2013	153,403	532,190	4,914	38,405	370,522	821,734	0	53,968	266,244
2014	203,074	627,846	5,750	40,224	387,921	918,422	28,289	67,524	362,555
2015	288,855	688,564	5,750	42,726	416,599	977,209	28,289	101,357	465,238
2016	325,660	781,005	5,750	43,180	440,998	1,057,210	28,289	112,052	494,328
2017	366,099	891,943	5,750	56,787	440,998	1,075,299	28,289	126,464	494,328
2018	537,761	991,962	5,750	56,947	450,628	1,155,072	56,543	136,360	552,650
2019	626,228	1,049,303	5,750	57,350	471,103	1,210,587	56,543	140,921	635,655
2020	686,128	1,073,328	5,750	57,960	483,730	1,210,587	74,212	185,158	674,136
2021	759,893	1,089,569	5,750	62,363	483,730	1,210,587	74,212	261,299	682,185
2022	811,187	1,137,733	5,750	71,476	495,077	1,210,587	100,094	452,670	774,643
2023	811,187	1,251,663	5,750	71,476	495,077	1,210,587	100,094	494,183	784,434
2024	878,274	1,278,591	5,750	71,476	495,077	1,210,587	100,094	506,794	803,467

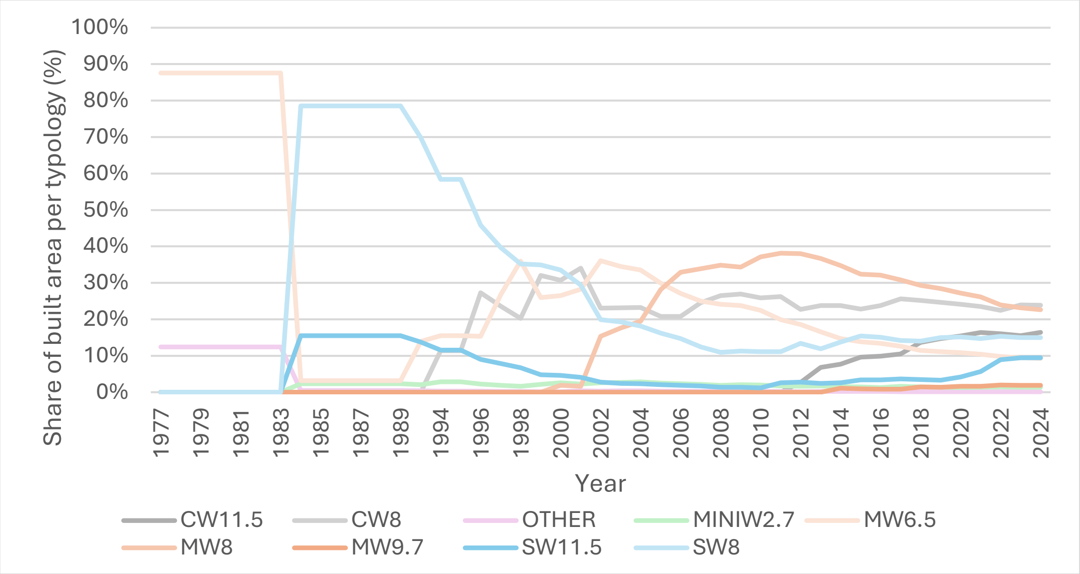

Figure A. 6. Share of built area by warehouse typology (1977–2024), expressed as a percentage of the annual stock surviving in 2024.

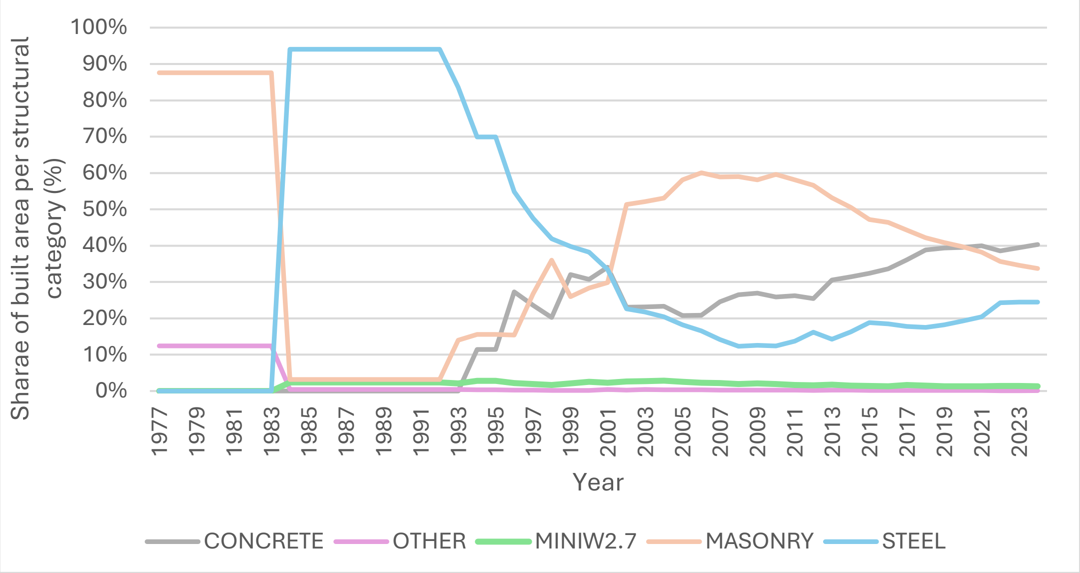

Figure A. 7. Share of built area by structural category (1977–2024), expressed as a percentage of the annual stock surviving in 2024.

Table A. 9. Annual share of built area by warehouse typology, expressed as a percentage of the annual stock surviving in 2024.

Year	CW11.5	CW8	OTHER	MINIW2.7	MW6.5	MW8	MW9.7	SW11.5	SW8
1977	0%	0%	12%	0%	88%	0%	0%	0%	0%
1978	0%	0%	12%	0%	88%	0%	0%	0%	0%
1979	0%	0%	12%	0%	88%	0%	0%	0%	0%
1980	0%	0%	12%	0%	88%	0%	0%	0%	0%
1981	0%	0%	12%	0%	88%	0%	0%	0%	0%
1982	0%	0%	12%	0%	88%	0%	0%	0%	0%
1983	0%	0%	12%	0%	88%	0%	0%	0%	0%
1984	0%	0%	0%	2%	3%	0%	0%	15%	79%
1985	0%	0%	0%	2%	3%	0%	0%	15%	79%
1986	0%	0%	0%	2%	3%	0%	0%	15%	79%
1987	0%	0%	0%	2%	3%	0%	0%	15%	79%
1988	0%	0%	0%	2%	3%	0%	0%	15%	79%
1989	0%	0%	0%	2%	3%	0%	0%	15%	79%
1990	0%	0%	0%	2%	3%	0%	0%	15%	79%
1991	0%	0%	0%	2%	3%	0%	0%	15%	79%
1992	0%	0%	0%	2%	3%	0%	0%	15%	79%
1993	0%	0%	0%	2%	14%	0%	0%	14%	70%
1994	0%	11%	0%	3%	16%	0%	0%	12%	58%
1995	0%	11%	0%	3%	16%	0%	0%	12%	58%
1996	0%	27%	0%	2%	15%	0%	0%	9%	46%
1997	0%	24%	0%	2%	27%	0%	0%	8%	40%
1998	0%	20%	0%	2%	36%	0%	0%	7%	35%
1999	0%	32%	0%	2%	26%	0%	0%	5%	35%
2000	0%	31%	0%	3%	26%	2%	0%	5%	34%
2001	0%	34%	0%	2%	28%	2%	0%	4%	29%
2002	0%	23%	0%	3%	36%	15%	0%	3%	20%
2003	0%	23%	0%	3%	34%	18%	0%	2%	19%
2004	0%	23%	0%	3%	34%	20%	0%	2%	18%
2005	0%	21%	0%	3%	30%	28%	0%	2%	16%
2006	0%	21%	0%	2%	27%	33%	0%	2%	15%
2007	0%	25%	0%	2%	25%	34%	0%	2%	12%
2008	0%	26%	0%	2%	24%	35%	0%	1%	11%
2009	0%	27%	0%	2%	24%	34%	0%	1%	11%
2010	0%	26%	0%	2%	22%	37%	0%	1%	11%
2011	0%	26%	0%	2%	20%	38%	0%	3%	11%
2012	3%	23%	0%	2%	19%	38%	0%	3%	13%
2013	7%	24%	0%	2%	17%	37%	0%	2%	12%
2014	8%	24%	0%	2%	15%	35%	1%	3%	14%
2015	10%	23%	0%	1%	14%	32%	1%	3%	15%
2016	10%	24%	0%	1%	13%	32%	1%	3%	15%
2017	11%	26%	0%	2%	13%	31%	1%	4%	14%
2018	14%	25%	0%	1%	11%	29%	1%	3%	14%
2019	15%	25%	0%	1%	11%	28%	1%	3%	15%
2020	15%	24%	0%	1%	11%	27%	2%	4%	15%
2021	16%	24%	0%	1%	10%	26%	2%	6%	15%
2022	16%	22%	0%	1%	10%	24%	2%	9%	15%
2023	16%	24%	0%	1%	9%	23%	2%	9%	15%
2024	16%	24%	0%	1%	9%	23%	2%	9%	15%

Table A. 10. Annual share of built area by structural category, expressed as a percentage of the annual stock surviving in 2024.

Year	CONCRETE	OTHER	MINIW2.7	MASONRY	STEEL
1977	0%	12%	0%	88%	0%
1978	0%	12%	0%	88%	0%
1979	0%	12%	0%	88%	0%
1980	0%	12%	0%	88%	0%
1981	0%	12%	0%	88%	0%
1982	0%	12%	0%	88%	0%
1983	0%	12%	0%	88%	0%
1984	0%	0%	2%	3%	94%
1985	0%	0%	2%	3%	94%
1986	0%	0%	2%	3%	94%
1987	0%	0%	2%	3%	94%
1988	0%	0%	2%	3%	94%
1989	0%	0%	2%	3%	94%
1990	0%	0%	2%	3%	94%
1991	0%	0%	2%	3%	94%
1992	0%	0%	2%	3%	94%
1993	0%	0%	2%	14%	84%
1994	11%	0%	3%	16%	70%
1995	11%	0%	3%	16%	70%
1996	27%	0%	2%	15%	55%
1997	24%	0%	2%	27%	48%
1998	20%	0%	2%	36%	42%
1999	32%	0%	2%	26%	40%
2000	31%	0%	3%	28%	38%
2001	34%	0%	2%	30%	33%
2002	23%	0%	3%	51%	23%
2003	23%	0%	3%	52%	22%
2004	23%	0%	3%	53%	20%
2005	21%	0%	3%	58%	18%
2006	21%	0%	2%	60%	17%
2007	25%	0%	2%	59%	14%
2008	26%	0%	2%	59%	12%
2009	27%	0%	2%	58%	13%
2010	26%	0%	2%	60%	12%
2011	26%	0%	2%	58%	14%
2012	25%	0%	2%	57%	16%
2013	31%	0%	2%	53%	14%
2014	31%	0%	2%	51%	16%
2015	32%	0%	1%	47%	19%
2016	34%	0%	1%	46%	18%
2017	36%	0%	2%	44%	18%
2018	39%	0%	1%	42%	17%
2019	39%	0%	1%	41%	18%
2020	40%	0%	1%	40%	19%
2021	40%	0%	1%	38%	20%
2022	39%	0%	1%	36%	24%
2023	39%	0%	1%	35%	24%
2024	40%	0%	1%	34%	24%

Table A. 11. Material intensity variables and corresponding GIS codes. Variables are grouped into aggregated (by material) and component-level categories.

Category	Variable description	MI Code
Aggregated (by material)	Material Intensity – Total Steel	MI_S
	Material Intensity – Total Concrete	MI_C
	Material Intensity – Total Brick	MI_B
	Material Intensity – Total Masonry	MI_M
	Material Intensity – Total Others	MI_O
Component level	Material Intensity – Roof – Steel Structure	MI_R_SS
	Material Intensity – Roof – Metal Panels	MI_R_MP
	Material Intensity – Walls & Columns – Brick	MI_WC_B
	Material Intensity – Walls & Columns – Masonry	MI_WC_M
	Material Intensity – Walls & Columns – Steel Structure	MI_WC_SS
	Material Intensity – Walls & Columns – Concrete	MI_WC_C
	Material Intensity – Walls & Columns – Steel Reinforcement	MI_WC_SR
	Material Intensity – Walls & Columns – Metal Panels	MI_WC_MP
	Material Intensity – Floor – Concrete	MI_F_C
	Material Intensity – Floor – Steel Reinforcement	MI_F_SR
	Material Intensity – Others – Other Components	MI_O_O

Table A. 12. Material intensities (in kg/m^2) by component and subcomponent for each warehouse typology.

Typology code	Roof structure		Walls & Columns						Floor		Others	Total
	MI_R_SS	MI_R_MP	MI_WC_B	MI_WC_M	MI_WC_SS	MI_WC_C	MI_WC_SR	MI_WC_MP	MI_F_C	MI_F_SR	MI_O_O	
MW9.7	14	4	38	29	-	635	8	-	432	-	1	1,161
MW8	14	4	33	24	-	450	4	-	360	-	1	889
MW6.5	14	4	28	19	-	376	3	-	360	-	1	805
MINIW2.7	6	4	-	-	14	-	-	4	360	-	-	388
CW11.5	30	4	-	-	7	166	6	4	432	-	1	649
CW8	30	4	-	-	6	146	3	3	432	-	1	623
SW11.5	19	4	-	-	12	127	3	2	500	-	1	669
SW8	19	4	-	-	8	89	2	2	500	-	1	625

Table A. 13. Material intensities (in kg/m^2) by component group for each warehouse typology.

Typology code	Roof structure	Walls & Columns	Floor	Others	Total
MW9.7	18	710	432	1	1,161
MW8	18	511	360	1	889
MW6.5	18	426	360	1	805
MINIW2.7	10	19	360	-	388
CW11.5	33	182	432	1	649
CW8	33	157	432	1	623
SW11.5	23	145	500	1	669
SW8	23	101	500	1	625

Table A. 14. Material intensities (in kg/m^2) by material category for each warehouse typology.

Typology code	Metal	Concrete	Masonry		Others	Total
	MI_S	MI_C	MI_B	MI_M	MI_O	
MW9.7	26	1,067	38	29	1	1,161
MW8	22	810	33	24	1	889
MW6.5	21	736	28	19	1	805
MINIW2.7	28	360	-	-	-	388
CW11.5	50	598	-	-	1	649
CW8	45	578	-	-	1	623
SW11.5	41	628	-	-	1	669
SW8	35	589	-	-	1	625

A.6. Supporting tables for material stock quantification

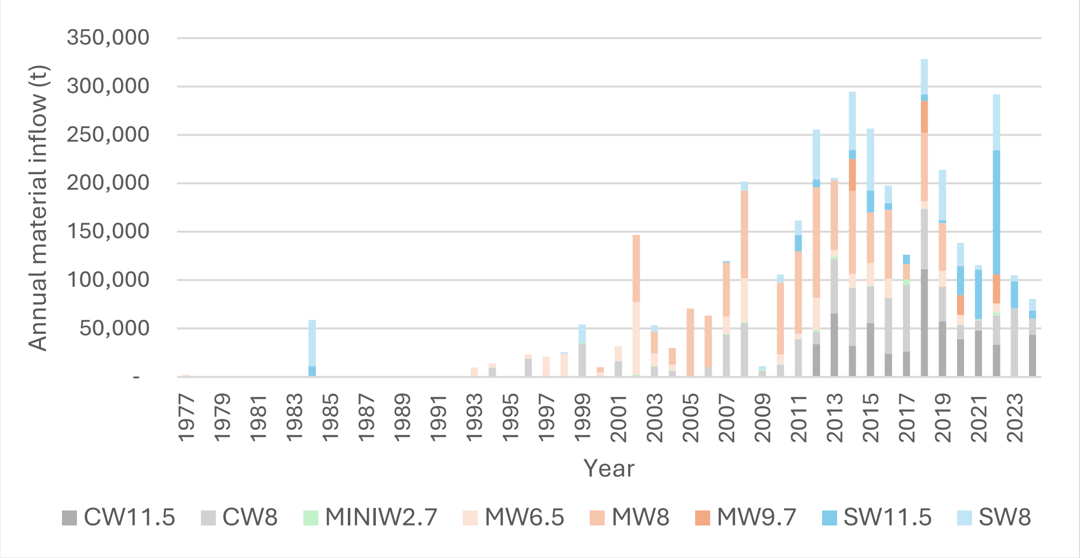

Figure A. 8. Annual material inflow by typology (1977–2024), expressed in tonnes (t). The figure shows the total quantity of materials entering the logistic sector each year according to their corresponding typology.

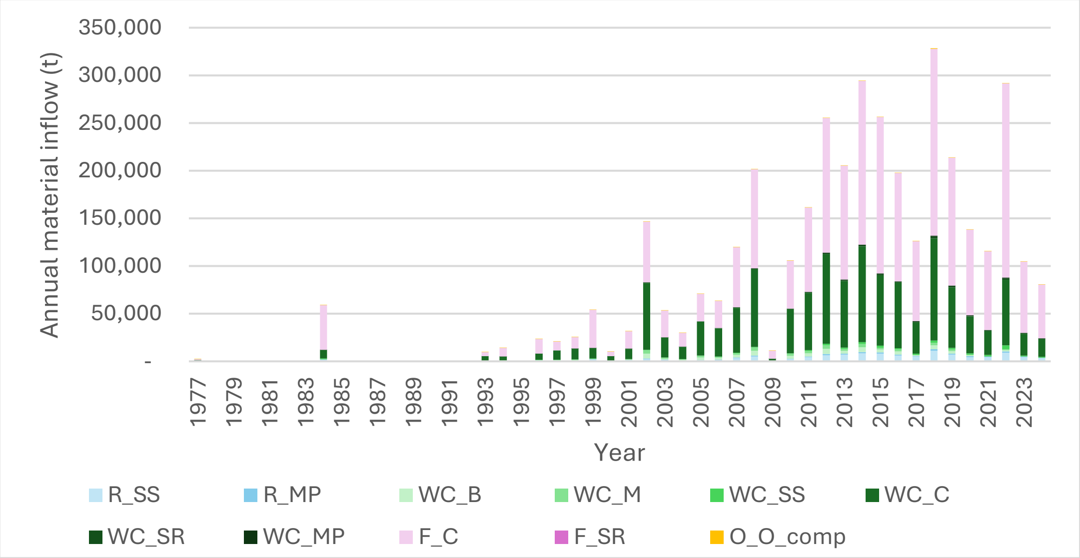

Figure A. 9. Annual material inflow by material and structural component (1977–2024), expressed in tonnes (t). The figure shows the total quantity of materials entering each structural component of the logistic sector per year.

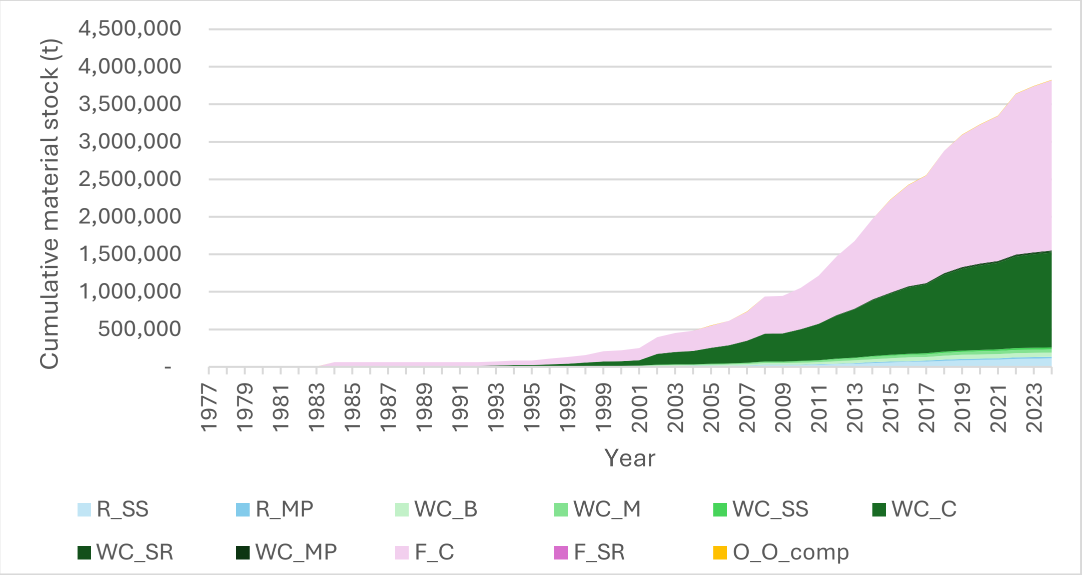

Figure A. 10. Cumulative MS by material and structural component (1977–2024), expressed in tonnes (t). The figure shows the accumulation of materials within each structural component over time.

Table A. 15. Historic material inflow by warehouse typology (1977–2024), expressed in tonnes (t). The table shows the annual quantity of materials entering the logistic sector, disaggregated by structural typology.

Year	CW11.5	CW8	MINIW2.7	MW6.5	MW8	MW9.7	SW11.5	SW8	Annual inflow
1977	-	-	-	2,491	-	-	-	-	2,491
1978	-	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-	-
1984	-	-	886	-	-	-	10,143	48,014	59,043
1985	-	-	-	-	-	-	-	-	-
1986	-	-	-	-	-	-	-	-	-
1987	-	-	-	-	-	-	-	-	-
1988	-	-	-	-	-	-	-	-	-
1989	-	-	-	-	-	-	-	-	-
1990	-	-	-	-	-	-	-	-	-
1991	-	-	-	-	-	-	-	-	-
1992	-	-	-	-	-	-	-	-	-
1993	-	-	-	9,881	-	-	-	-	9,881
1994	-	9,355	556	4,096	-	-	-	-	14,007
1995	-	-	-	-	-	-	-	-	-
1996	-	19,143	-	4,240	-	-	-	-	23,383
1997	-	-	-	20,921	-	-	-	-	20,921
1998	-	-	-	23,917	-	-	-	1,741	25,657
1999	-	34,121	1,128	-	-	-	-	18,746	53,995
2000	-	-	688	4,060	5,477	-	-	-	10,226
2001	-	16,484	-	15,076	-	-	-	-	31,560
2002	-	-	2,374	75,058	69,417	-	-	-	146,850
2003	-	10,685	852	12,855	22,624	-	-	6,501	53,516
2004	-	6,145	827	5,875	17,120	-	-	-	29,966
2005	-	-	-	-	70,781	-	-	-	70,781
2006	-	10,086	-	-	53,438	-	-	-	63,524
2007	-	43,555	884	17,911	55,631	-	1,222	887	120,090
2008	-	55,433	1,024	45,198	90,636	-	-	9,417	201,708
2009	-	6,582	940	-	-	-	-	3,455	10,976
2010	-	12,671	456	10,171	74,197	-	-	8,268	105,762
2011	-	38,749	-	5,892	85,388	-	16,608	14,956	161,593
2012	33,829	12,855	1,522	33,510	114,292	-	8,151	51,606	255,764
2013	65,657	55,889	2,782	7,000	71,537	-	-	2,864	205,729
2014	32,213	59,629	707	14,001	85,958	32,837	9,074	60,213	294,630
2015	55,632	37,850	972	23,077	52,263	-	22,646	64,196	256,636
2016	23,869	57,625	176	19,633	71,122	-	7,159	18,187	197,772
2017	26,226	69,155	5,286	-	16,081	-	9,647	-	126,396
2018	111,328	62,349	62	7,749	70,920	32,796	6,624	36,462	328,290
2019	57,374	35,745	157	16,476	49,354	-	3,053	51,894	214,051
2020	38,847	14,976	237	10,161	-	20,509	29,610	24,058	138,399
2021	47,839	10,124	1,711	-	-	-	50,966	5,032	115,671
2022	33,266	30,024	3,540	9,131	-	30,043	128,096	57,804	291,903
2023	-	71,021	-	-	-	-	27,787	6,121	104,929
2024	43,508	16,786	-	-	-	-	8,441	11,899	80,635
Total	**569,587**	**797,035**	**27,768**	**398,379**	**1,076,236**	**116,185**	**339,228**	**502,320**	**3,826,737**

Table A. 16. Historic material inflow by material category (1977–2024), expressed in tonnes (t). The table summarises the annual inflow of materials aggregated by material type.

Year	ME_S	CO_C	MA_B	MA_M	O_O
1977	65	2,279	85	59	3
1978	-	-	-	-	-
1979	-	-	-	-	-
1980	-	-	-	-	-
1981	-	-	-	-	-
1982	-	-	-	-	-
1983	-	-	-	-	-
1984	3,394	55,555	-	-	94
1985	-	-	-	-	-
1986	-	-	-	-	-
1987	-	-	-	-	-
1988	-	-	-	-	-
1989	-	-	-	-	-
1990	-	-	-	-	-
1991	-	-	-	-	-
1992	-	-	-	-	-
1993	256	9,040	339	236	10
1994	819	12,930	140	98	19
1995	-	-	-	-	-
1996	1,485	21,616	145	101	36
1997	543	19,140	717	499	21
1998	719	23,520	820	571	27
1999	3,592	50,317	-	-	86
2000	288	9,340	343	245	9
2001	1,575	29,066	517	360	42
2002	3,802	134,083	5,159	3,665	141
2003	2,078	49,175	1,283	917	62
2004	1,069	27,424	839	602	32
2005	1,713	64,456	2,636	1,911	65
2006	2,018	58,007	1,990	1,443	66
2007	5,129	110,202	2,686	1,929	144
2008	7,955	185,067	4,925	3,525	236
2009	737	10,223	-	-	16
2010	3,470	96,821	3,112	2,246	113
2011	6,858	148,709	3,382	2,446	198
2012	10,670	235,492	5,406	3,885	310
2013	11,317	189,138	2,904	2,098	273
2014	13,922	272,103	4,758	3,469	377
2015	13,914	237,662	2,738	1,962	360
2016	9,672	182,132	3,322	2,388	258
2017	8,337	116,842	599	434	184
2018	18,106	302,846	3,982	2,913	443
2019	11,708	197,915	2,403	1,725	300
2020	7,942	128,490	1,021	751	195
2021	7,897	107,597	-	-	178
2022	16,919	272,302	1,298	963	421
2023	7,136	97,624	-	-	169
2024	5,720	74,786	-	-	128
Total	**190,826**	**3,531,900**	**57,551**	**41,442**	**5,017**

Table A. 17. Historic material inflow by material and structural component (1977–2024), expressed in tonnes (t). The table presents the annual quantity of materials entering the logistic sector, disaggregated by both material type and structural component.

Year	R_ SS	R_ MP	WC_ B	WC_ M	WC_ SS	WC_ C	WC_ SR	WC_ MP	F_ C	F_ SR	O_O_ comp
1977	43	11	85	59	-	1,165	10	-	1,115	-	3
1978	-	-	-	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-	-	-	-
1984	1,797	342	-	-	861	8,737	233	162	46,818	-	94
1985	-	-	-	-	-	-	-	-	-	-	-
1986	-	-	-	-	-	-	-	-	-	-	-
1987	-	-	-	-	-	-	-	-	-	-	-
1988	-	-	-	-	-	-	-	-	-	-	-
1989	-	-	-	-	-	-	-	-	-	-	-
1990	-	-	-	-	-	-	-	-	-	-	-
1991	-	-	-	-	-	-	-	-	-	-	-
1992	-	-	-	-	-	-	-	-	-	-	-
1993	172	45	339	236	-	4,619	40	-	4,420	-	10
1994	524	78	140	98	106	4,100	66	45	8,831	-	19
1995	-	-	-	-	-	-	-	-	-	-	-
1996	983	131	145	101	175	6,453	118	79	15,163	-	36
1997	364	94	717	499	-	9,781	84	-	9,360	-	21
1998	470	118	820	571	23	11,428	103	4	12,093	-	27
1999	2,220	318	-	-	605	10,626	250	199	39,690	-	86
2000	168	47	343	245	25	4,668	40	8	4,672	-	9
2001	1,045	164	517	360	150	10,898	147	68	18,168	-	42
2002	2,438	644	5,159	3,665	88	70,194	605	27	63,890	-	141
2003	1,303	258	1,283	917	216	20,867	231	69	28,308	-	62
2004	677	140	839	602	87	12,839	131	35	14,586	-	32
2005	1,115	289	2,636	1,911	-	35,793	309	-	28,662	-	65
2006	1,321	277	1,990	1,443	92	29,379	286	41	28,629	-	66
2007	3,334	582	2,686	1,929	464	47,036	554	195	63,166	-	144
2008	5,157	961	4,925	3,525	670	81,245	905	262	103,822	-	236
2009	435	67	-	-	141	2,027	48	46	8,196	-	16
2010	2,212	475	3,112	2,246	244	46,407	463	78	50,414	-	113
2011	4,234	778	3,382	2,446	854	60,265	741	251	88,444	-	198
2012	6,400	1,240	5,406	3,885	1,387	93,985	1,226	416	141,507	-	310
2013	7,035	1,059	2,904	2,098	1,376	69,701	1,206	640	119,437	-	273
2014	8,439	1,450	4,758	3,469	1,899	100,417	1,521	614	171,686	-	377
2015	8,226	1,354	2,738	1,962	2,267	73,698	1,352	715	163,964	-	360
2016	6,064	994	3,322	2,388	1,170	68,649	1,001	443	113,483	-	258
2017	5,099	717	599	434	1,290	32,827	707	524	84,015	-	184
2018	11,017	1,662	3,982	2,913	2,410	106,907	2,018	1,000	195,939	-	443
2019	7,082	1,124	2,403	1,725	1,718	63,622	1,171	612	134,293	-	300
2020	4,517	717	1,021	751	1,432	38,459	834	442	90,031	-	195
2021	4,325	648	-	-	1,671	25,016	739	514	82,581	-	178
2022	9,026	1,560	1,298	963	3,860	68,813	1,553	919	203,489	-	421
2023	4,368	600	-	-	1,232	22,743	538	399	74,881	-	169
2024	3,397	456	-	-	946	18,343	548	373	56,443	-	128
Total	**115,009**	**19,400**	**57,551**	**41,442**	**27,460**	**1,261,704**	**19,778**	**9,179**	**2,270,195**	**-**	**5,017**

Table A. 18. Cumulative MS by warehouse typology (1977–2024), expressed in tonnes (t). The table shows the accumulated quantity of materials within the logistic sector, disaggregated by structural typology.

Year	CW11.5	CW8	MINIW2.7	MW6.5	MW8	MW9.7	SW11.5	SW8	Total Stock
1977	-	-	-	2,491	-	-	-	-	2,491
1978	-	-	-	2,491	-	-	-	-	2,491
1979	-	-	-	2,491	-	-	-	-	2,491
1980	-	-	-	2,491	-	-	-	-	2,491
1981	-	-	-	2,491	-	-	-	-	2,491
1982	-	-	-	2,491	-	-	-	-	2,491
1983	-	-	-	2,491	-	-	-	-	2,491
1984	-	-	886	2,491	-	-	10,143	48,014	61,534
1985	-	-	886	2,491	-	-	10,143	48,014	61,534
1986	-	-	886	2,491	-	-	10,143	48,014	61,534
1987	-	-	886	2,491	-	-	10,143	48,014	61,534
1988	-	-	886	2,491	-	-	10,143	48,014	61,534
1989	-	-	886	2,491	-	-	10,143	48,014	61,534
1990	-	-	886	2,491	-	-	10,143	48,014	61,534
1991	-	-	886	2,491	-	-	10,143	48,014	61,534
1992	-	-	886	2,491	-	-	10,143	48,014	61,534
1993	-	-	886	12,372	-	-	10,143	48,014	71,415
1994	-	9,355	1,442	16,468	-	-	10,143	48,014	85,422
1995	-	9,355	1,442	16,468	-	-	10,143	48,014	85,422
1996	-	28,498	1,442	20,708	-	-	10,143	48,014	108,805
1997	-	28,498	1,442	41,629	-	-	10,143	48,014	129,726
1998	-	28,498	1,442	65,545	-	-	10,143	49,754	155,383
1999	-	62,619	2,570	65,545	-	-	10,143	68,500	209,379
2000	-	62,619	3,259	69,606	5,477	-	10,143	68,500	219,605
2001	-	79,104	3,259	84,681	5,477	-	10,143	68,500	251,165
2002	-	79,104	5,633	159,739	74,895	-	10,143	68,500	398,014
2003	-	89,789	6,484	172,594	97,518	-	10,143	75,001	451,530
2004	-	95,934	7,311	178,469	114,638	-	10,143	75,001	481,497
2005	-	95,934	7,311	178,469	185,419	-	10,143	75,001	552,278
2006	-	106,019	7,311	178,469	238,857	-	10,143	75,001	615,801
2007	-	149,575	8,196	196,381	294,489	-	11,365	75,887	735,892
2008	-	205,007	9,220	241,579	385,125	-	11,365	85,304	937,600
2009	-	211,589	10,160	241,579	385,125	-	11,365	88,759	948,577
2010	-	224,259	10,616	251,750	459,322	-	11,365	97,027	1,054,339
2011	-	263,008	10,616	257,642	544,710	-	27,973	111,983	1,215,932
2012	33,829	275,862	12,138	291,152	659,001	-	36,124	163,589	1,471,695
2013	99,486	331,751	14,920	298,152	730,538	-	36,124	166,453	1,677,424
2014	131,700	391,380	15,627	312,152	816,496	32,837	45,198	226,666	1,972,055
2015	187,331	429,230	16,599	335,229	868,758	32,837	67,844	290,862	2,228,690
2016	211,200	486,855	16,775	354,862	939,881	32,837	75,003	309,049	2,426,462
2017	237,426	556,011	22,061	354,862	955,962	32,837	84,650	309,049	2,552,858
2018	348,754	618,359	22,123	362,611	1,026,882	65,633	91,274	345,511	2,881,148
2019	406,128	654,104	22,280	379,087	1,076,236	65,633	94,327	397,405	3,095,200
2020	444,975	669,080	22,517	389,248	1,076,236	86,142	123,937	421,463	3,233,599
2021	492,813	679,205	24,227	389,248	1,076,236	86,142	174,903	426,495	3,349,270
2022	526,079	709,229	27,768	398,379	1,076,236	116,185	302,999	484,299	3,641,173
2023	526,079	780,249	27,768	398,379	1,076,236	116,185	330,786	490,420	3,746,102
2024	**569,587**	**797,035**	**27,768**	**398,379**	**1,076,236**	**116,185**	**339,228**	**502,320**	**3,826,737**

Table A. 19. Cumulative MS by material category (1977–2024), expressed in tonnes (t). The table summarises the accumulated quantity of materials aggregated by material type.

Year	ME_S	CO_C	MA_B	MA_M	O_O
1977	65	2,279	85	59	3
1978	65	2,279	85	59	3
1979	65	2,279	85	59	3
1980	65	2,279	85	59	3
1981	65	2,279	85	59	3
1982	65	2,279	85	59	3
1983	65	2,279	85	59	3
1984	3,459	57,834	85	59	96
1985	3,459	57,834	85	59	96
1986	3,459	57,834	85	59	96
1987	3,459	57,834	85	59	96
1988	3,459	57,834	85	59	96
1989	3,459	57,834	85	59	96
1990	3,459	57,834	85	59	96
1991	3,459	57,834	85	59	96
1992	3,459	57,834	85	59	96
1993	3,715	66,874	424	295	106
1994	4,534	79,804	565	393	126
1995	4,534	79,804	565	393	126
1996	6,019	101,420	710	494	162
1997	6,562	120,560	1,427	993	183
1998	7,281	144,081	2,247	1,564	210
1999	10,873	194,397	2,247	1,564	296
2000	11,162	203,738	2,591	1,809	306
2001	12,737	232,804	3,107	2,168	348
2002	16,539	366,887	8,266	5,833	489
2003	18,617	416,062	9,550	6,751	551
2004	19,686	443,486	10,389	7,353	582
2005	21,399	507,942	13,025	9,264	648
2006	23,417	565,949	15,015	10,707	713
2007	28,546	676,151	17,701	12,636	858
2008	36,501	861,218	22,626	16,161	1,093
2009	37,238	871,442	22,626	16,161	1,110
2010	40,708	968,263	25,738	18,407	1,223
2011	47,566	1,116,972	29,121	20,852	1,421
2012	58,237	1,352,464	34,526	24,737	1,731
2013	69,553	1,541,602	37,430	26,836	2,004
2014	83,476	1,813,705	42,188	30,305	2,381
2015	97,390	2,051,367	44,926	32,266	2,741
2016	107,061	2,233,499	48,248	34,655	2,999
2017	115,398	2,350,341	48,847	35,089	3,183
2018	133,504	2,653,186	52,829	38,002	3,626
2019	145,212	2,851,101	55,232	39,728	3,927
2020	153,155	2,979,591	56,253	40,479	4,121
2021	161,051	3,087,188	56,253	40,479	4,299
2022	177,970	3,359,490	57,551	41,442	4,720
2023	185,106	3,457,113	57,551	41,442	4,889
2024	**190,826**	**3,531,900**	**57,551**	**41,442**	**5,017**

Table A. 20. Cumulative MS by material and structural component (1977–2024), expressed in tonnes (t). The table presents the accumulated quantity of materials within the logistic sector, disaggregated by both material type and structural component.

Year	**R_SS**	**R_MP**	**WC_B**	**WC_M**	**WC_SS**	**WC_C**	**WC_SR**	**WC_MP**	**F_C**	**F_SR**	**O_O_comp**
1977	43	11	85	59	-	1,165	10	-	1,115	-	3
1978	43	11	85	59	-	1,165	10	-	1,115	-	3
1979	43	11	85	59	-	1,165	10	-	1,115	-	3
1980	43	11	85	59	-	1,165	10	-	1,115	-	3
1981	43	11	85	59	-	1,165	10	-	1,115	-	3
1982	43	11	85	59	-	1,165	10	-	1,115	-	3
1983	43	11	85	59	-	1,165	10	-	1,115	-	3
1984	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1985	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1986	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1987	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1988	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1989	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1990	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1991	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1992	1,840	353	85	59	861	9,902	243	162	47,932	-	96
1993	2,012	398	424	295	861	14,521	282	162	52,353	-	106
1994	2,537	476	565	393	967	18,621	348	207	61,183	-	126
1995	2,537	476	565	393	967	18,621	348	207	61,183	-	126
1996	3,520	607	710	494	1,142	25,074	466	285	76,347	-	162
1997	3,884	701	1,427	993	1,142	34,854	550	285	85,706	-	183
1998	4,355	819	2,247	1,564	1,165	46,282	653	289	97,799	-	210
1999	6,575	1,137	2,247	1,564	1,770	56,908	903	488	137,489	-	296
2000	6,743	1,184	2,591	1,809	1,795	61,576	944	496	142,162	-	306
2001	7,788	1,348	3,107	2,168	1,946	72,474	1,091	564	160,330	-	348
2002	10,226	1,992	8,266	5,833	2,034	142,668	1,696	590	224,220	-	489
2003	11,529	2,251	9,550	6,751	2,250	163,535	1,927	660	252,527	-	551
2004	12,206	2,391	10,389	7,353	2,336	176,374	2,058	694	267,113	-	582
2005	13,322	2,680	13,025	9,264	2,336	212,167	2,367	694	295,775	-	648
2006	14,643	2,957	15,015	10,707	2,429	241,546	2,653	736	324,403	-	713
2007	17,977	3,538	17,701	12,636	2,893	288,582	3,207	931	387,570	-	858
2008	23,134	4,499	22,626	16,161	3,563	369,826	4,112	1,193	491,392	-	1,093
2009	23,569	4,566	22,626	16,161	3,704	371,853	4,159	1,239	499,588	-	1,110
2010	25,780	5,041	25,738	18,407	3,948	418,260	4,622	1,317	550,003	-	1,223
2011	30,014	5,819	29,121	20,852	4,802	478,525	5,363	1,568	638,447	-	1,421
2012	36,414	7,059	34,526	24,737	6,190	572,510	6,589	1,984	779,954	-	1,731
2013	43,449	8,118	37,430	26,836	7,566	642,211	7,796	2,624	899,391	-	2,004
2014	51,888	9,568	42,188	30,305	9,465	742,629	9,316	3,238	1,071,077	-	2,381
2015	60,114	10,922	44,926	32,266	11,732	816,327	10,669	3,953	1,235,040	-	2,741
2016	66,178	11,916	48,248	34,655	12,901	884,976	11,670	4,396	1,348,523	-	2,999
2017	71,277	12,633	48,847	35,089	14,191	917,803	12,377	4,920	1,432,538	-	3,183
2018	82,293	14,295	52,829	38,002	16,601	1,024,710	14,395	5,920	1,628,476	-	3,626
2019	89,376	15,419	55,232	39,728	18,319	1,088,332	15,566	6,533	1,762,769	-	3,927
2020	93,893	16,136	56,253	40,479	19,751	1,126,790	16,400	6,975	1,852,800	-	4,121
2021	98,217	16,785	56,253	40,479	21,422	1,151,806	17,139	7,488	1,935,382	-	4,299
2022	107,243	18,344	57,551	41,442	25,283	1,220,619	18,692	8,407	2,138,871	-	4,720
2023	111,612	18,944	57,551	41,442	26,515	1,243,361	19,230	8,806	2,213,752	-	4,889
2024	**115,009**	**19,400**	**57,551**	**41,442**	**27,460**	**1,261,704**	**19,778**	**9,179**	**2,270,195**	**-**	**5,017**

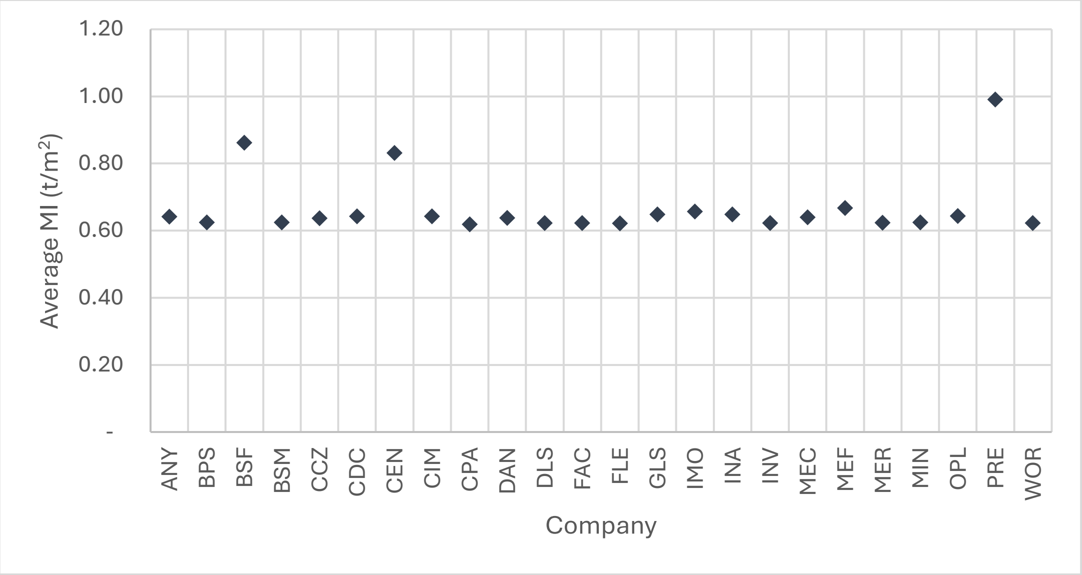

Figure A. 11. Average MI per company, expressed in tonnes per square metre (t/m^2). Paved areas within each LC are not considered in these values.

A.7. Supporting tables for spatial distribution results

Table A. 21. Distribution of LC by total MS range, expressed in tonnes (t).

Total MS (t)	Number of LC	Share of total LC (%)	Share of total MS (%)
0 – 40,000	23	35%	14%
40,000 - 80,000	24	37%	24%
80,000 - 120,000	7	11%	12%
120,000 - 160,000	4	6%	11%
> 160,000	7	11%	39%
Total	**65**	**100%**	100%

Table A. 22. Total MS by LC, including both built and paved areas, expressed in tonnes (t).

LC	Built area MS	Paved area MS	Total MS
ANY_Colo Colo	21,704	7,586	29,290
ANY_Lo Boza	41,124	14,991	56,115
ANY_Lo Echevers	46,656	13,784	60,441
ANY_Lo Echevers 400	24,419	7,181	31,600
ANY_Miraflores	39,438	12,451	51,889
BPS_Puerta Sur	74,788	25,347	100,136
BSF_Huingan	30,670	9,297	39,968
BSF_La Farfana	348,326	117,469	465,794
BSF_Laguna Sur	185,937	39,286	225,223
BSF_Lo Aguirre	159,619	40,346	199,966
BSF_Lo Echevers	88,095	20,017	108,112
BSF_Lo Espejo	69,363	16,564	85,927
BSF_Los Mares	41,392	10,278	51,670
BSF_Puerto Madero	365,792	87,972	453,764
BSF_Vespucio	154,081	25,316	179,397
BSM_Noviciados	16,573	6,820	23,393
BSM_Quilicura	33,912	13,351	47,263
CCZ_Lo Boza Lascar	21,857	6,787	28,644
CCZ_Logicentro Miraf	19,499	6,310	25,809
CCZ_Logicentro SPF	14,902	9,023	23,925
CDC_Enea 1	108,294	35,518	143,811
CDC_La Divisa	22,646	8,700	31,347
CDC_Loginsa	18,379	4,382	22,761
CDC_San Bernardo	69,649	27,027	96,676
CEN_Casas Viejas	28,000	8,816	36,815
CEN_La Vara	33,772	14,018	47,790
CEN_Nos	32,519	11,381	43,900
CIM_Gral Velasquez	36,253	10,023	46,276
CIM_Lascar	20,409	8,549	28,959
CIM_Licancabur	42,331	21,482	63,813
CPA_Quilicura 1	28,136	17,309	45,445
CPA_Quilicura 2	16,709	5,136	21,845
DAN_Lo Boza	27,018	10,955	37,973
DAN_Miraflores	38,247	13,369	51,616
DLS_Bodepark	26,867	13,793	40,659
DLS_Centro Pudahuel	53,973	24,629	78,602
FAC_Caupolican	25,966	9,836	35,801
FLE_ENEA 1	99,524	41,593	141,117
FLE_ENEA 2	118,139	35,803	153,942
FLE_Lo Boza 120	62,792	20,165	82,957
FLE_Lo Boza 422	52,493	16,833	69,327
FLE_Lo Boza 441	27,311	8,786	36,097
FLE_Puerto Vespucio	19,143	8,888	28,031
GLS_Lo Espejo	62,763	18,528	81,291
IMO_Imolog	19,544	8,737	28,282
INA_Pto Stgo	28,437	13,432	41,869
INV_El Cerro	28,807	11,195	40,002
MEC_Aeroparque	126,116	76,063	202,179
MEC_Buenaventura	200,934	89,970	290,904
MEC_Carrascal	28,745	18,769	47,514
MEC_Cordillera	54,268	23,245	77,513
MEC_ENEA	36,462	17,300	53,762
MEC_Miraflores	53,447	39,610	93,057
MEC_Miraflores III	24,001	15,432	39,433
MEC_Noviciado	24,235	12,504	36,739
MEC_San Bernardo	31,714	19,302	51,016
MEF_Colina	22,122	8,662	30,785
MER_Lo Espejo	73,645	55,875	129,520
MIN_Lo Espejo	22,705	4,476	27,181
OPL_ENEA 1	29,659	11,124	40,784
OPL_Laguna Sur	37,583	15,014	52,597
PRE_Lo Boza	40,439	11,679	52,118
PRE_San Bernardo	32,912	9,815	42,727
WOR_Workcenter Miraf	22,940	9,830	32,770
WOR_Workcenter Vespu	18,538	8,559	27,097
Total	**3,826,737**	**1,366,289**	**5,193,025**

Table A. 23. Weighted average year of construction per LC, also used to define the representative year for paved areas.

LC	Weighted average year of construction
ANY_Colo Colo	2,024
ANY_Lo Boza	2,017
ANY_Lo Echevers	2,016
ANY_Lo Echevers 400	2,020
ANY_Miraflores	2,014
BPS_Puerta Sur	2,017
BSF_Huingan	2,020
BSF_La Farfana	2,013
BSF_Laguna Sur	2,010
BSF_Lo Aguirre	2,018
BSF_Lo Echevers	2,002
BSF_Lo Espejo	1,996
BSF_Los Mares	2,022
BSF_Puerto Madero	2,005
BSF_Vespucio	2,016
BSM_Noviciados	2,021
BSM_Quilicura	2,014
CCZ_Lo Boza Lascar	2,011
CCZ_Logicentro Miraf	2,015
CCZ_Logicentro SPF	2,011
CDC_Enea 1	2,020
CDC_La Divisa	2,022
CDC_Loginsa	2,015
CDC_San Bernardo	2,021
CEN_Casas Viejas	2,013
CEN_La Vara	2,008
CEN_Nos	2,017
CIM_Gral Velasquez	2,013
CIM_Lascar	2,012
CIM_Licancabur	2,022
CPA_Quilicura 1	1,998
CPA_Quilicura 2	2,006
DAN_Lo Boza	2,008
DAN_Miraflores	2,013
DLS_Bodepark	2,016
DLS_Centro Pudahuel	2,019
FAC_Caupolican	2,005
FLE_ENEA 1	2,014
FLE_ENEA 2	2,017
FLE_Lo Boza 120	2,008
FLE_Lo Boza 422	2,023
FLE_Lo Boza 441	2,011
FLE_Puerto Vespucio	1,996
GLS_Lo Espejo	2,019
IMO_Imolog	2,015
INA_Pto Stgo	2,019
INV_El Cerro	2,016
MEC_Aeroparque	2,018
MEC_Buenaventura	2,021
MEC_Carrascal	2,009
MEC_Cordillera	1,984
MEC_ENEA	2,018
MEC_Miraflores	2,013
MEC_Miraflores III	2,020
MEC_Noviciado	2,017
MEC_San Bernardo	2,010
MEF_Colina	2,016
MER_Lo Espejo	2,008
MIN_Lo Espejo	2,019
OPL_ENEA 1	2,023
OPL_Laguna Sur	2,005
PRE_Lo Boza	2,002
PRE_San Bernardo	2,014
WOR_Workcenter Miraf	2,016
WOR_Workcenter Vespu	2,020

Appendix B – Dynamic Material Flow Analysis

B.1 Methodological background and modelling choices for MFA

Methodological approaches in MFA

In static MFA models, balancing equations allow outputs to be computed from inputs, or vice versa. In contrast, dynamic models treat variables as functions of time, enabling the analysis of temporal changes (de Haes & Heijungs, 2009).

When it comes to modelling MFA, two main approaches can be distinguished: flow-driven and the stock-driven model, depending on what drives changes in the system. In the first case, inflows and outflows are the drivers, and stocks result from the interplay between them. In this sense, inflow and outflow data, as well as definition on how materials leave the system, are used to calculate how the stock evolves over time. Future inflows may be determined through assumptions or derived from socio-economic factors (Hu, 2010). In contrast, a stock-driven model, assumes that the stock of the service units in use is the main driver and the corresponding flows are dependent on it and its lifetime (Müller, 2006). Here the stocks can be estimated through expansion rates, development patterns, or as functions of population and their lifestyle (Hu, 2010; Müller, 2006).

These assessments can also be classified depending on whether they address future events or analyse past stocks and flows. It is possible also to have a combination of these two retrospective and prospective approaches. Another common distinction refers to how material stocks are derived. In top-down MFA, stocks are calculated as the difference between inflows and outflows, whereas bottom-up MFA estimates them directly by summing the materials quantities in a specific period of time (Müller et al., 2014).

From an EOL perspective, demolition activity determines the rate at which building stocks are replaced (Gallardo et al., 2014). Two main modelling approaches are used for this: the leaching model and the delay model. The first one is applied if the age distribution of the stock is not relevant and all elements have the same chance of being discarded. In this case, a fixed demolition rate proportional to the total stock is assumed (van der Voet et al., 2002). In contrast, the delay model considers the lifetime of materials in use, where outflows are estimated based on historical inflows and lifetime distributions (Müller, 2006). In this sense, the leaching approach considers the stock as homogenous, whereas the delay model tracks cohorts ages and prevents them from being demolished before their EOL (Pauliuk et al., 2013; van der Voet et al., 2002).

As a tool, MFA can be applied in a wide range of contexts, scales, and objectives, from national studies to sectoral analyses, and from single substances to groups of materials. According to de Haes and Heijungs (2009) there is no standardised procedure for its application, however most studies share three main elements: system definition, quantification of the stocks and flows, and interpretation of results (van der Voet, 2002). First, the definition stage sets the boundaries of the system in terms of space, function, time, and materials. The second stage involves data collection and processing to develop the model, which can take the form of accounting, static, or dynamic modelling. Finally, interpretation stage focuses on evaluating the robustness of the quantification and translating the results into policy-relevant terms, as highlighted by van der Voet (2002).

Data availability and lifetime assumptions in the Chilean context

In Chile, there is a method to estimate the service life of new or existing buildings, described in the standard NCh3447:2020 (Instituto Nacional de Normalización (INN), 2019). However, this methodology is labour-intensive and requires detailed information at the component level, as well as specific data on use and performance conditions. Therefore, its application is intended for individual projects rather than for sectoral-scale assessments, as in the case of this study. Moreover, the standard focuses on providing a technical service life estimate and assessing whether a building can be expected to reach its design life. Due to the time required, the high level of data detail, and its focus on technical lifespan (without considering socio-economic variables) its application was disregarded in this study.

Previous stock and flow studies in Chile also highlight structural limitations in the availability of empirical data. Gallardo et al. (2014) applied a stock and flow assessment in Chile to analyse the dynamics of the residential sector, aiming to evaluate how the building stock behaved when including earthquake damage to the system. Their model did not consider MS quantification, instead assessed how the total stock of floor area changed over time due to this vulnerability. They used a fixed demolition rate linked to the stock time series, as this approach offered greater flexibility to represent the effects of earthquakes, which are not directly linked to building age or lifetime. Gallardo et al. (2014) also noted the lack of empirical data on outflows in Chile, where demolition activity is not systematically recorded. This has not changed in the past years, as information is still usually managed by the Municipal Building Authority (Dirección de Obras Municipales, DOM), with records kept mainly in physical form, with historical data available through in-person requests or published in aggregated formats. As a result, large-scale assessments remain unfeasible, as it would require visiting each municipality where warehouses may have existed, identifying relevant blocks, and manually reviewing or purchasing building and demolition permits. This limitation is even greater as informal construction remains common and official permits are not always requested for every type of work.

Beyond country-specific data constraints, the selection of lifetime assumptions is further shaped by broader methodological limitations recognised in literature. Hu et al. (2010) point out the relevance of lifetime parameters, yet they remain poorly characterised in most cases. Similarly, Müller (2006) also notes that knowledge about building lifetimes is generally limited. The situation is similar for NRBs, with even less attention to data development for this category. Müller et al. (2014) further highlight that the average lifetime plays a more decisive role in the results than the chosen distribution or the assumed standard deviation.

B.2 Data integration and processing workflow for dynamic Material Flow Analysis

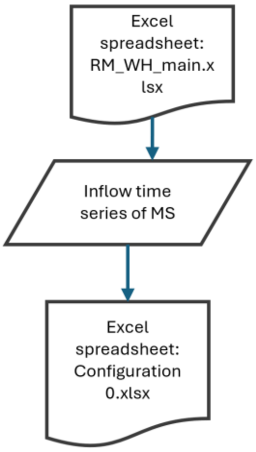

Figure B. 1. Processing workflow indicating the main steps, data sources, and output files used for the calculation of the dynamic MFA with deterministic lifespan (Configuration 0).

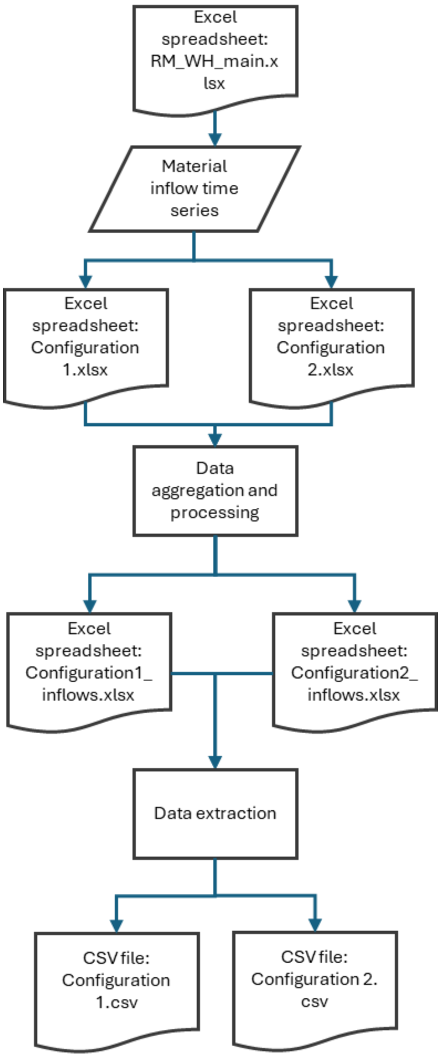

Figure B. 2. Processing workflow indicating the main steps, data sources, and output files used for the initial data processing of the dynamic MFA with probabilistic lifetime distributions (Configurations 1 and 2).

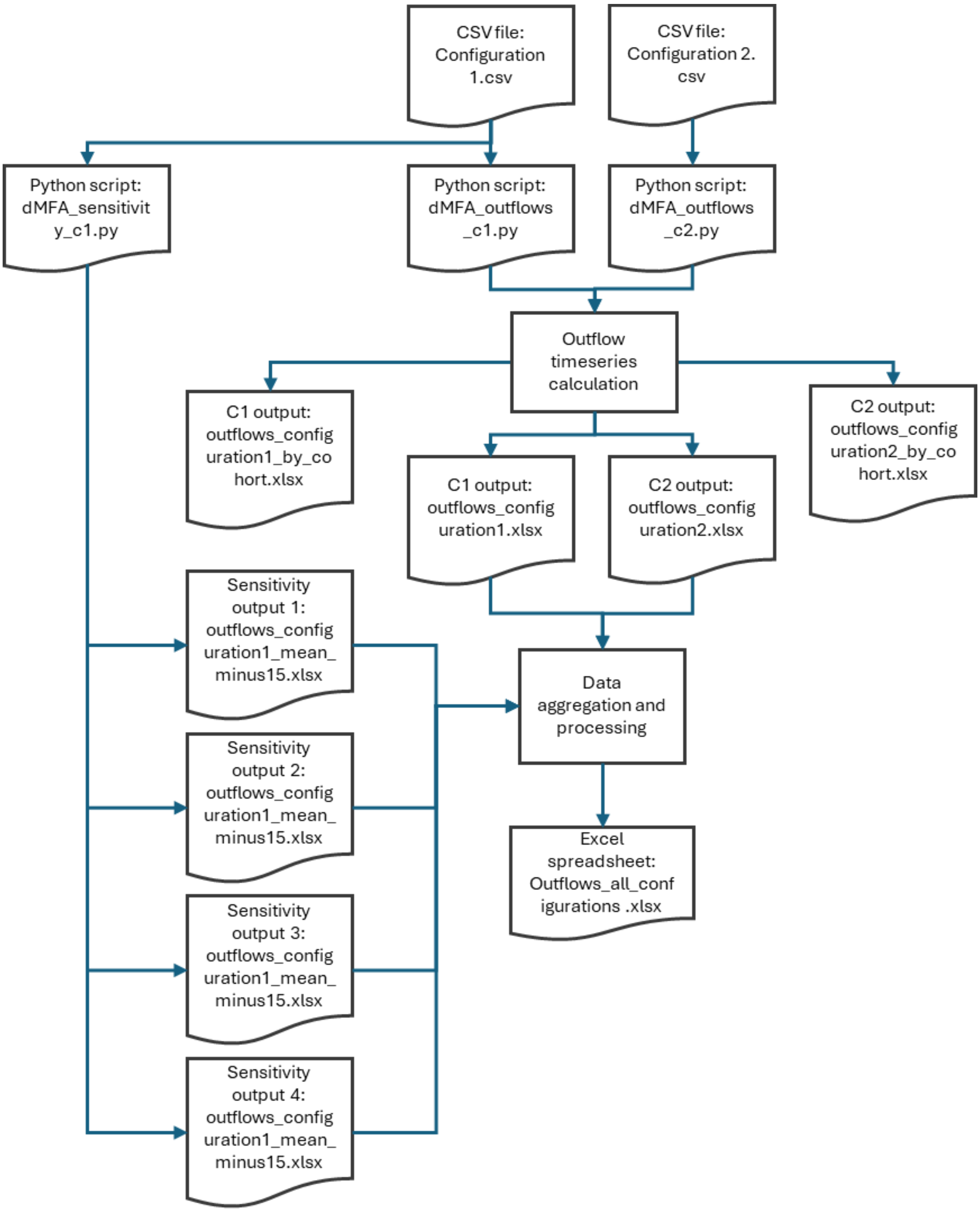

Figure B. 3. Processing workflow indicating the main steps, data sources, and output files used for the calculation of outflow curves from the dynamic model.

B.3 Material outflows by component under a fixed lifetime assumption

Table B. 1. Material outflows per decade disaggregated by component, corresponding to the totals reported in Table 5.

Decade	R_SS	R_MP	WC_B	WC_M	WC_SS	WC_C	WC_SR	WC_MP	F_C	F_SR	O_O_comp	Total outflow (t)
2030-2039	43	11	85	59	-	1,165	10	-	1,115	-	3	2,491
2040-2049	1,797	342	-	-	861	8,737	233	162	46,818	-	94	59,043
2050-2059	4,734	784	2,162	1,504	909	47,006	661	327	89,557	-	200	147,844
2060-2069	16,994	3,429	20,379	14,597	1,934	314,945	3,256	751	362,099	-	813	739,198
2070-2079	65,807	10,853	32,606	23,567	14,615	716,479	11,406	5,293	1,263,181	-	2,817	2,146,623
2080-2089	25,633	3,981	2,319	1,715	9,141	173,373	4,212	2,647	507,426	-	1,091	731,537

B.4 Difference in Material Stock and Outflow Values Between Table 4 and Table 6

The difference between tables stems from the way aggregation was carried out in QGIS. In ***Table 4***, centre-level aggregation led to *BSF_Laguna Sur* LC being classified entirely within Pudahuel. In contrast, ***Table 6*** aggregates outflows by the actual municipality of each warehouse, not by complete logistics centres, so individual warehouses may fall in different municipalities. This difference accounts for about 2% of the sector's total material stock. The specific warehouses involved are listed in ***Table B. 2***.

Table B. 2. Warehouses classified as part of Pudahuel in the aggregated MS analysis (Chapter 3.4) and as part of Maipú in the municipal outflow analysis (Chapter 3.5).

WH id code (in QGIS)	Total MS (t)
BSF_Lagu_1	26,223
BSF_Lagu_7	25,237
BSF_Lagu_8	5,892
BSF_Lagu_2	9,077
BSF_Lagu_9	8,182
BSF_Lagu_10	9,252
Total	**83,862**

B.5 Comparison of probabilistic modelling configurations

This section provides additional evidence supporting the selection of the probabilistic modelling approach adopted in the main analysis and includes supplementary tables of inflows and outflows for both configurations that support the interpretation of the main results. As shown in ***Figure B. 4***, inflows under Configuration 2 (C2) show more pronounced peaks and variations than Configuration 1 (C1). This results from the aggregation of construction years at the logistics-centre level in C2, where materials from multiple warehouses are assigned to a single representative year per centre. In contrast, C1 distributes inflows across the individual construction years of each warehouse, resulting in a smoother inflow time series. In addition, C2 includes approximately 1.37 million tonnes of additional inflows from shared paved areas. The complete historical inflow time series used as model input is reported in ***Table B. 3***.

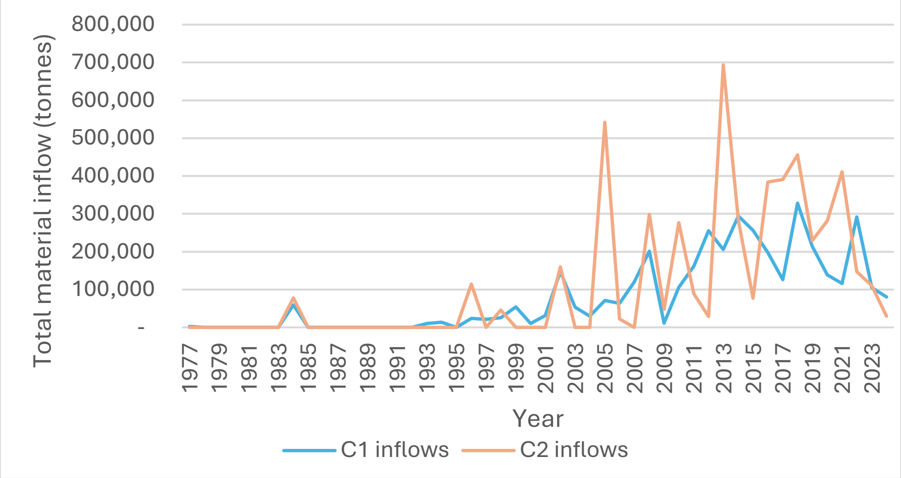

Figure B. 4. Comparison of annual material inflows under Configuration 1 (C1) and Configuration 2 (C2) (1977-2024), expressed in tonnes.

Table B. 3. Annual material inflows for Configuration 1 (C1) and Configuration 2 (C2) used as model inputs, expressed in tonnes (t).

Year	C1 inflows	C2 inflows
1977	2,491	-
1978	-	-
1979	-	-
1980	-	-
1981	-	-
1982	-	-
1983	-	-
1984	59,043	77,513
1985	-	-
1986	-	-
1987	-	-
1988	-	-
1989	-	-
1990	-	-
1991	-	-
1992	-	-
1993	9,881	-
1994	14,007	-
1995	-	-
1996	23,383	113,958
1997	20,921	-
1998	25,657	45,445
1999	53,995	-
2000	10,226	-
2001	31,560	-
2002	146,850	160,230
2003	53,516	-
2004	29,966	-
2005	70,781	542,163
2006	63,524	21,845
2007	120,090	-
2008	201,708	298,240
2009	10,976	47,514
2010	105,762	276,239
2011	161,593	88,667
2012	255,764	28,959
2013	205,729	693,558
2014	294,630	282,996
2015	256,636	76,852
2016	197,772	384,053
2017	126,396	390,832
2018	328,290	455,906
2019	214,051	228,943
2020	138,399	281,910
2021	115,671	410,973
2022	291,903	146,830
2023	104,929	110,110
2024	80,635	29,290

Despite the differences in the input parameters, both configurations produce very similar outflow dynamics, as shown in ***Figure B. 5***. Although C2 inflows are more concentrated in specific years, their superposition with the probabilistic lifetime distributions smooths these differences over time. As a result, both configurations generate bell-shaped outflow curves that are symmetrically centred, with a peak in 2075, as also presented in ***Table B. 4***. The main difference between the resulting curves lies in the magnitude of the outflows, which includes shared paved areas in Configuration 2, rather than by differences in the timing of outflows. A similar behaviour is observed when analysing the evolution of the remaining material stock (see ***Table B. 5***). The years at which 80%, 50%, and 10% of the initial stock remain in the system are identical for both configurations. This confirms that, under a normal probabilistic lifetime assumption and for the sector and period analysed, increased input granularity has a limited effect on the timing of material releases. This suggests that, when warehouse-level construction data are unavailable, using representative construction years at the LC level allows temporal outflow dynamics to be reasonably approximated.

Figure B. 6 presents annual material outflows by component under Configuration 2. Outflows are dominated by concrete elements, mainly walls and columns (WC_C) and floor concrete (F_C), with the inclusion of floor concrete from shared paved areas (F_C_PA), which is not present in Configuration 1. The corresponding outflow profile for Configuration 1 is presented in the main Results section of the thesis (**Section 3.5.2**).

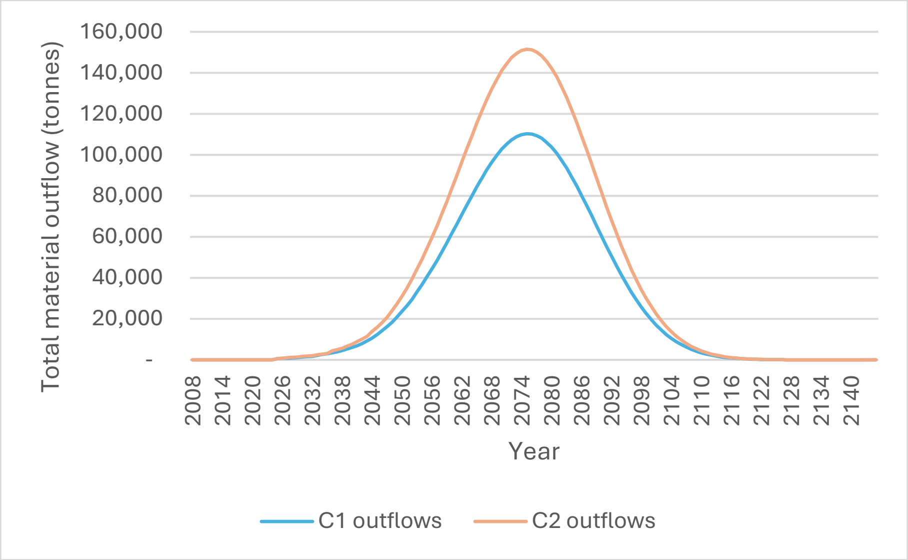

Figure B. 5. Total annual material outflows under Configuration 1 (C1) and Configuration 2 (C2) (2008-2145), expressed in tonnes (t).

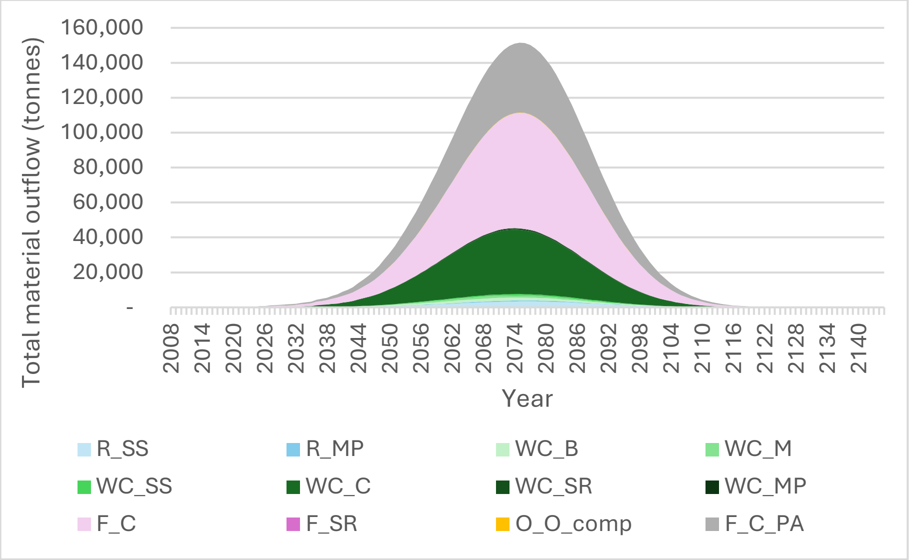

Figure B. 6. Annual material outflows by component under Configuration 2 (2008-2145), expressed in tonnes (t).

Table B. 4. Annual material outflows for Configuration 1 (C1) and Configuration 2 (C2), expressed in tonnes (t) (2024–2145).

Year	C1 outflows	C2 outflows
2024	-	-
2025	603	672
2026	691	769
2027	820	1,042
2028	962	1,193
2029	1,125	1,425
2030	1,348	1,619
2031	1,535	1,829
2032	1,770	2,054
2033	2,197	2,531
2034	2,552	2,840
2035	2,913	3,172
2036	3,371	4,323
2037	3,871	4,912
2038	4,509	5,532
2039	5,345	6,647
2040	6,014	7,553
2041	6,886	8,892
2042	7,937	10,133
2043	9,249	11,422
2044	10,654	13,812
2045	12,354	15,948
2046	14,207	18,039
2047	16,190	20,790
2048	18,281	23,871
2049	20,871	27,394
2050	23,573	30,976
2051	26,423	34,981
2052	29,484	39,549
2053	33,045	44,160
2054	36,631	49,074
2055	40,427	54,212
2056	44,334	59,612
2057	48,431	65,287
2058	52,697	71,206
2059	57,105	77,331
2060	61,622	83,617
2061	66,212	90,011
2062	70,832	96,453
2063	75,435	102,878
2064	79,972	109,214
2065	84,390	115,386
2066	88,632	121,316
2067	92,643	126,923
2068	96,367	132,128
2069	99,748	136,853
2070	102,736	141,026
2071	105,281	144,576
2072	107,341	147,445
2073	108,879	149,581
2074	109,866	150,943
2075	**110,282**	**151,502**
2076	110,114	151,242
2077	109,360	150,161
2078	108,028	148,269
2079	106,133	145,591
2080	103,702	142,165
2081	100,769	138,040
2082	97,376	133,277
2083	93,573	127,946
2084	89,413	122,124
2085	84,954	115,896
2086	80,259	109,346
2087	75,390	102,565
2088	70,409	95,640
2089	65,376	88,656
2090	60,350	81,694
2091	55,385	74,830
2092	50,530	68,132
2093	45,828	61,661
2094	41,318	55,466
2095	37,029	49,591
2096	32,987	44,068
2097	29,210	38,920
2098	25,710	34,162
2099	22,492	29,801
2100	19,557	25,835
2101	16,901	22,259
2102	14,517	19,057
2103	12,392	16,215
2104	10,514	13,709
2105	8,865	11,518
2106	7,428	9,616
2107	6,185	7,978
2108	5,118	6,576
2109	4,209	5,387
2110	3,440	4,384
2111	2,793	3,545
2112	2,254	2,849
2113	1,807	2,274
2114	1,440	1,804
2115	1,140	1,422
2116	897	1,113
2117	701	866
2118	544	669
2119	420	514
2120	322	392
2121	245	297
2122	186	224
2123	140	168
2124	104	124
2125	77	92
2126	57	67
2127	42	49
2128	30	36
2129	22	26
2130	16	18
2131	11	13
2132	8	9
2133	6	6
2134	4	4
2135	3	3
2136	2	2
2137	1	1
2138	1	1
2139	1	1
2140	0	0
2141	0	0
2142	0	0
2143	0	0
2144	0	0
2145	0	0

Table B. 5. Annual remaining material stock and share of initial stock for Configuration 1 (C1) and Configuration 2 (C2), expressed in tonnes (t) (2024–2145).

Year	Stock C1	Initial MS %	Stock C2	Initial MS %
2024	3,826,737	100%	5,193,025	100%
2025	3,826,134	100%	5,192,354	100%
2026	3,825,443	100%	5,191,584	100%
2027	3,824,622	100%	5,190,542	100%
2028	3,823,661	100%	5,189,349	100%
2029	3,822,536	100%	5,187,923	100%
2030	3,821,188	100%	5,186,305	100%
2031	3,819,653	100%	5,184,476	100%
2032	3,817,883	100%	5,182,422	100%
2033	3,815,686	100%	5,179,891	100%
2034	3,813,134	100%	5,177,051	100%
2035	3,810,221	100%	5,173,880	100%
2036	3,806,850	99%	5,169,557	100%
2037	3,802,980	99%	5,164,645	99%
2038	3,798,471	99%	5,159,113	99%
2039	3,793,126	99%	5,152,467	99%
2040	3,787,112	99%	5,144,913	99%
2041	3,780,226	99%	5,136,022	99%
2042	3,772,289	99%	5,125,888	99%
2043	3,763,040	98%	5,114,466	98%
2044	3,752,386	98%	5,100,654	98%
2045	3,740,033	98%	5,084,706	98%
2046	3,725,826	97%	5,066,667	98%
2047	3,709,636	97%	5,045,877	97%
2048	3,691,355	96%	5,022,007	97%
2049	3,670,484	96%	4,994,613	96%
2050	3,646,911	95%	4,963,637	96%
2051	3,620,488	95%	4,928,656	95%
2052	3,591,004	94%	4,889,106	94%
2053	3,557,959	93%	4,844,947	93%
2054	3,521,328	92%	4,795,873	92%
2055	3,480,901	91%	4,741,662	91%
2056	3,436,568	90%	4,682,049	90%
2057	3,388,137	89%	4,616,762	89%
2058	3,335,440	87%	4,545,556	88%
2059	3,278,335	86%	4,468,224	86%
2060	3,216,712	84%	4,384,607	84%
2061	3,150,500	82%	4,294,597	83%
2062	**3,079,668**	**80%**	**4,198,144**	**81%**
2063	**3,004,233**	**79%**	**4,095,266**	**79%**
2064	2,924,260	76%	3,986,051	77%
2065	2,839,871	74%	3,870,665	75%
2066	2,751,239	72%	3,749,350	72%
2067	2,658,596	69%	3,622,427	70%
2068	2,562,229	67%	3,490,299	67%
2069	2,462,481	64%	3,353,446	65%
2070	2,359,745	62%	3,212,420	62%
2071	2,254,465	59%	3,067,844	59%
2072	2,147,124	56%	2,920,398	56%
2073	2,038,245	53%	2,770,817	53%
2074	**1,928,379**	**50%**	**2,619,874**	**50%**
2075	**1,818,097**	**48%**	**2,468,371**	**48%**
2076	1,707,983	45%	2,317,129	45%
2077	1,598,623	42%	2,166,968	42%
2078	1,490,595	39%	2,018,698	39%
2079	1,384,462	36%	1,873,107	36%
2080	1,280,760	33%	1,730,942	33%
2081	1,179,991	31%	1,592,901	31%
2082	1,082,615	28%	1,459,624	28%
2083	989,042	26%	1,331,678	26%
2084	899,630	24%	1,209,553	23%
2085	814,675	21%	1,093,658	21%
2086	734,416	19%	984,312	19%
2087	659,025	17%	881,747	17%
2088	588,616	15%	786,107	15%
2089	523,240	14%	697,451	13%
2090	462,890	12%	615,757	12%
2091	**407,504**	**11%**	**540,927**	**10%**
2092	**356,974**	**9%**	**472,795**	**9%**
2093	311,146	8%	411,134	8%
2094	269,828	7%	355,668	7%
2095	232,799	6%	306,077	6%
2096	199,811	5%	262,009	5%
2097	170,601	4%	223,089	4%
2098	144,891	4%	188,927	4%
2099	122,399	3%	159,126	3%
2100	102,843	3%	133,291	3%
2101	85,941	2%	111,032	2%
2102	71,424	2%	91,975	2%
2103	59,032	2%	75,760	1%
2104	48,518	1%	62,051	1%
2105	39,654	1%	50,533	1%
2106	32,226	1%	40,917	1%
2107	26,041	1%	32,939	1%
2108	20,922	1%	26,363	1%
2109	16,713	0%	20,976	0%
2110	13,274	0%	16,592	0%
2111	10,481	0%	13,047	0%
2112	8,227	0%	10,198	0%
2113	6,420	0%	7,924	0%
2114	4,980	0%	6,120	0%
2115	3,840	0%	4,698	0%
2116	2,943	0%	3,585	0%
2117	2,242	0%	2,718	0%
2118	1,698	0%	2,049	0%
2119	1,278	0%	1,535	0%
2120	956	0%	1,143	0%
2121	711	0%	845	0%
2122	525	0%	621	0%
2123	386	0%	454	0%
2124	281	0%	329	0%
2125	204	0%	237	0%
2126	147	0%	170	0%
2127	105	0%	121	0%
2128	75	0%	85	0%
2129	53	0%	60	0%
2130	37	0%	42	0%
2131	25	0%	29	0%
2132	18	0%	20	0%
2133	12	0%	13	0%
2134	8	0%	9	0%
2135	5	0%	6	0%
2136	3	0%	4	0%
2137	2	0%	2	0%
2138	1	0%	1	0%
2139	1	0%	1	0%
2140	0	0%	0	0%
2141	0	0%	0	0%
2142	0	0%	0	0%
2143	0	0%	0	0%
2144	0	0%	0	0%
2145	0	0%	0	0%

Table B. 6. Decadal material outflows disaggregated by material component under Configuration 1, expressed in tonnes (t).

Decade	R_SS	R_MP	WC_B	WC_M	WC_SS	WC_C	WC_SR	WC_MP	F_C	F_SR	O_O_comp	Total
2000-2009	-	-	-	-	-	-	-	-	-	-	-	-
2010-2019	-	-	-	-	-	-	-	-	-	-	-	-
2020-2029	123	24	21	15	51	837	17	10	3,096	-	6	4,201
2030-2039	826	157	360	254	260	8,068	123	60	19,262	-	41	29,409
2040-2049	3,248	613	2,383	1,699	697	43,007	543	203	70,096	-	153	122,643
2050-2059	10,681	1,933	7,785	5,578	2,099	142,614	1,867	709	218,398	-	484	392,149
2060-2069	23,302	4,057	14,610	10,505	4,940	287,116	4,083	1,702	464,507	-	1,032	815,854
2070-2079	32,460	5,450	16,388	11,816	7,630	358,214	5,620	2,597	636,434	-	1,410	1,078,019
2080-2089	27,148	4,429	10,839	7,834	6,972	269,215	4,633	2,329	526,660	-	1,162	861,222
2090-2099	13,097	2,092	4,148	3,004	3,606	118,422	2,206	1,182	252,528	-	555	400,841
2100-2109	3,549	558	900	653	1,031	29,717	591	332	68,205	-	150	105,686
2110-2119	530	82	109	79	160	4,161	87	51	10,154	-	22	15,435
2120-2129	43	7	7	5	13	319	7	4	819	-	2	1,226
2130-2139	2	0	0	0	1	13	0	0	35	-	0	52
2140-2149	0	0	0	0	0	0	0	0	1	-	0	1

B.6 Exploratory assessment of substitution potential and sector expansion assumptions

The analysis presented in this appendix describes how the growth of the logistics sector is represented in order to estimate how the expected outflows from the 2024 stock could contribute to substituting primary material use within the logistics warehouse sector itself. Without developing a separate model to estimate future sectoral demand, and with the aim of providing orders of magnitude for future research, the behaviour of the sector is deliberately simplified.

As the logistics warehouse sector is relatively young and has experienced a phase of rapid expansion, historical growth rates are not expected to be sustained in the long term if extrapolated as percentage-based stock growth, as this would result in unrealistically large future stocks over extended time horizons. In addition, the historical record does not indicate a stable proportional relationship between the expansion of warehouse stock and other indicators, such as GDP or population. Simple diagnostic analyses conducted for the period 1996–2024 show weak and unstable associations between sectoral growth and these indicators, limiting their suitability as direct drivers for future projections. **Figure B. 7** illustrates the annual variation of warehouse stock, GDP, and population, showing that stock has grown at substantially higher and more variable rates. This is supported by **Table B. 7**, which shows that over the same period warehouse stock increased by a factor of more than 30, while GDP and population increased by less than a factor of three. In turn, yearly construction inflows exhibit a similar pattern of growth but with pronounced interannual volatility. In addition, the ratio between annual constructed area and GDP (m^2/CLP) does not display a stable behaviour (see **Figure B. 8**), even when analysing moving averages.

For these reasons, a robust understanding of future sectoral behaviour would require a more comprehensive analysis of the variables that effectively explain the evolution of the logistics sector, considering not only local drivers but also experiences from other contexts in which this industry has developed under comparable conditions. However, for the purpose of establishing orders of magnitude, this appendix adopts a conservative growth representation, with declining growth rates over time, to explore how current material stocks could contribute to future sectoral needs.

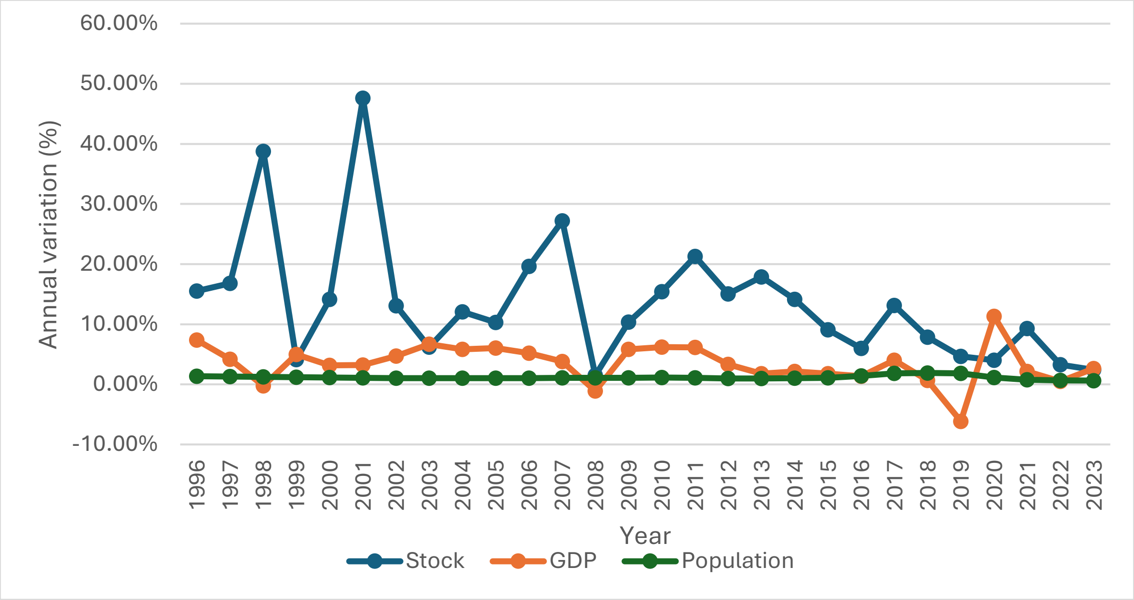

Figure B. 7. Annual variation of logistics warehouse stock, GDP, and population (1996–2023).

Table B. 7. Summary statistics of annual growth for inflows, stock, GDP, and population (1996–2024).

Variable	Inflows	Stock	GDP	Population
St. Dev	145.09%	10.46%	3.26%	0.30%
Growth factor	3.49	31.93	2.57	1.38
CAGR	4.57%	13.17%	3.43%	1.15%
Average	54%	14%	3%	1%

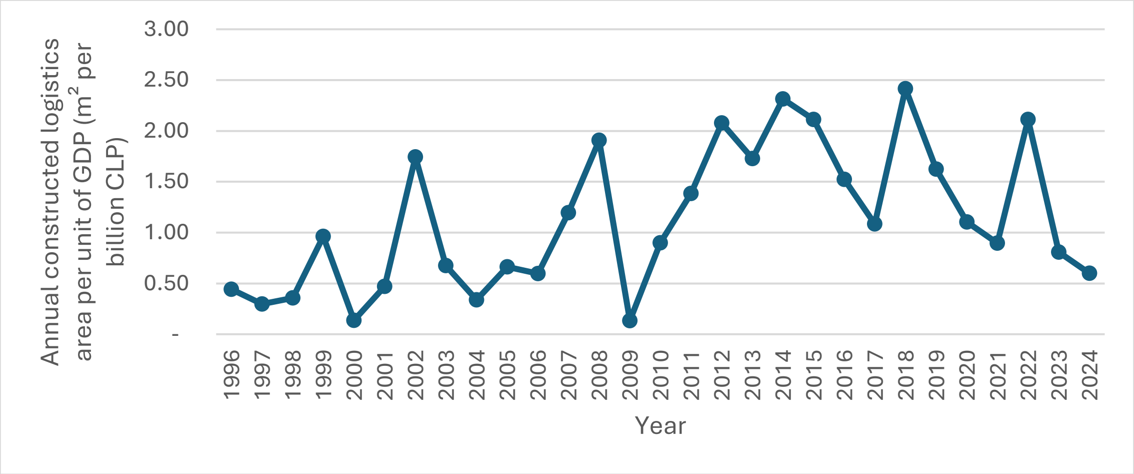

Figure B. 8. Annual logistics warehouse construction intensity relative to GDP (m^2 per billion CLP).

Accordingly, the average annual increase in logistics warehouse floor area observed between 1996 and 2024 is adopted as a fixed absolute increment, corresponding to an average stock growth of 185,091 m^2 per year (see **Table B. 8**). By definition, this implies a declining relative growth rate over time as the stock expands. This value is used to project the future construction flows required to sustain stock expansion while compensating for material outflows from the existing stock. Another important simplifying assumption of this exploratory analysis is that material outflows associated with buildings constructed after 2025 are not considered. While this does not reflect real-world dynamics, it is adopted to avoid the development of a separate dynamic material flow model.

Table B. 8. Key parameters used to represent historical sector growth.

Variable	Value
Total MS 2024 (t)	3,826,737
Total built area 2024 (m2)	5,350,110
Average MI (t/m2)	0.715
Projection base period	1996-2024
Annual growth (m2)	185,091
Annual growth (t)	132,389

Assuming that the sector maintains the current average MI factors in the future (calculated in section 2.1), the resulting annual net material addition is estimated at 132,389 tonnes. Over the period up to 2145, when outflows from the current stock are expected to be released, cumulative future material inflows remain below 20 million tonnes, of which less than 20% could theoretically be supplied by materials released from the existing stock (see **Table B. 9**). To avoid overstating future demand, the projected average annual material inflow remains below recent historical levels when expressed in material terms. As such, the estimated substitution potential reflects a conservative balance between projected outflows from the existing stock and simplified assumptions regarding future inflow requirements.

Table B. 9. Summary of projected growth, outflows, and future material needs.

Variable	Value
Expected growth (t)	16,019,068
Total outflows (t)	3,826,737
Future material needs (t)	19,845,805

As stated above, the results presented in this appendix do not account for technical, economic, regulatory, or organisational constraints and should therefore be interpreted as a highly exploratory upper bound, reflecting idealised conditions and simplified assumptions. Detailed calculations supporting this assessment are provided in SM 2.20.

Appendix C – Sensitivity Analysis

C.1. Justification of sensitivity parameter selection

In the stock quantification and characterisation, primary data were the main source of information. These data were either developed directly by the author or obtained through collaboration with industry stakeholders. Primary inputs included material quantities per warehouse, material intensity coefficients, and typologies classifications from site visits and publicly available information. Where building-specific documentation was unavailable, secondary data were used to complement the analysis.

In contrast, the MFA relied mainly on secondary data. Construction years were largely derived from historical Google satellite imagery for most companies, except for Bodegas San Francisco, for which construction dates were available at the warehouse or cluster level. Due to the absence of empirical service life data for the logistics sector, lifetime distributions and their parameters were adopted from the literature. While the assumed mean lifetime was based on values reported for the Chilean building sector, it does not come from logistics-specific empirical evidence, so it may not fully represent the sector's actual service life behaviour.

Given the key role of service life assumptions in determining both the timing and magnitude of material outflows, and their comparatively high level of uncertainty, the sensitivity analysis evaluates how changes in the assumed mean lifetime affect the model results.

C.2. Unaggregated annual material outflows

Table C. 1. Annual material outflows for the central probabilistic case and sensitivity cases (±15% and ±30% mean lifetime) (2008–2145), expressed in tonnes (t).

Year	Mean 60 years	+15% mean	-15% mean	+30% mean	-30% mean
2008	-	-	-	-	-
2009	-	-	-	-	-
2010	-	-	-	-	-
2011	-	-	-	-	-
2012	-	-	-	-	-
2013	-	-	-	-	-
2014	-	-	-	-	-
2015	-	-	-	-	-
2016	-	-	-	-	-
2017	-	-	-	-	-
2018	-	-	-	-	-
2019	-	-	-	-	-
2020	-	-	-	-	-
2021	-	-	-	-	-
2022	-	-	-	-	-
2023	-	-	-	-	-
2024	-	-	-	-	-
2025	603	226	1,743	93	5,227
2026	691	262	1,931	109	5,377
2027	820	316	2,234	132	5,897
2028	962	375	2,548	158	6,384
2029	1,125	445	2,905	188	6,969
2030	1,348	539	3,424	229	8,106
2031	1,535	623	3,790	267	8,567
2032	1,770	728	4,274	314	9,419
2033	2,197	907	5,345	394	12,456
2034	2,552	1,064	6,130	465	14,221
2035	2,913	1,229	6,884	541	15,718
2036	3,371	1,436	7,897	635	18,043
2037	3,871	1,664	8,983	741	20,427
2038	4,509	1,950	10,447	873	24,002
2039	5,345	2,318	12,473	1,042	29,388
2040	6,014	2,634	13,857	1,191	31,829
2041	6,886	3,035	15,789	1,380	35,940
2042	7,937	3,514	18,175	1,605	41,251
2043	9,249	4,103	21,259	1,881	48,604
2044	10,654	4,741	24,460	2,182	55,619
2045	12,354	5,506	28,413	2,542	64,664
2046	14,207	6,348	32,614	2,941	73,652
2047	16,190	7,262	36,945	3,377	82,040
2048	18,281	8,245	41,297	3,850	89,349
2049	20,871	9,444	46,899	4,424	100,282
2050	23,573	10,723	52,430	5,043	109,580
2051	26,423	12,100	57,961	5,716	117,515
2052	29,484	13,606	63,649	6,458	124,714
2053	33,045	15,354	70,383	7,320	134,639

Table C. 1 (continued).

Year	Mean 60 years	+15% mean	-15% mean	+30% mean	-30% mean
2054	36,631	17,178	76,563	8,233	141,076
2055	40,427	19,155	82,746	9,235	146,341
2056	44,334	21,258	88,576	10,317	149,221
2057	48,431	23,526	94,284	11,499	150,852
2058	52,697	25,961	99,784	12,787	151,162
2059	57,105	28,563	104,983	14,187	150,109
2060	61,622	31,331	109,792	15,701	147,693
2061	66,212	34,260	114,117	17,335	143,953
2062	70,832	37,343	117,875	19,091	138,965
2063	75,435	40,571	120,983	20,971	132,843
2064	79,972	43,930	123,373	22,977	125,733
2065	84,390	47,406	124,986	25,109	117,804
2066	88,632	50,979	125,778	27,365	109,246
2067	92,643	54,629	125,720	29,742	100,257
2068	96,367	58,330	124,802	32,237	91,040
2069	99,748	62,055	123,033	34,843	81,787
2070	102,736	65,776	120,437	37,553	72,681
2071	105,281	69,458	117,058	40,357	63,881
2072	107,341	73,070	112,957	43,244	55,525
2073	108,879	76,575	108,207	46,200	47,722
2074	109,866	79,938	102,897	49,211	40,550
2075	110,282	83,123	97,122	52,260	34,062
2076	110,114	86,094	90,985	55,329	28,282
2077	109,360	88,815	84,592	58,398	23,208
2078	108,028	91,255	78,049	61,445	18,821
2079	106,133	93,382	71,459	64,448	15,081
2080	103,702	95,169	64,919	67,384	11,940
2081	100,769	96,591	58,517	70,230	9,339
2082	97,376	97,628	52,332	72,960	7,215
2083	93,573	98,266	46,431	75,551	5,506
2084	89,413	98,492	40,866	77,980	4,150
2085	84,954	98,302	35,680	80,223	3,090
2086	80,259	97,696	30,901	82,258	2,271
2087	75,390	96,678	26,544	84,064	1,648
2088	70,409	95,261	22,616	85,624	1,181
2089	65,376	93,459	19,110	86,920	836
2090	60,350	91,293	16,015	87,938	584
2091	55,385	88,788	13,309	88,666	403
2092	50,530	85,973	10,968	89,096	274
2093	45,828	82,881	8,963	89,222	184
2094	41,318	79,548	7,263	89,040	122
2095	37,029	76,009	5,836	88,553	80
2096	32,987	72,304	4,649	87,763	52
2097	29,210	68,471	3,672	86,677	33
2098	25,710	64,550	2,875	85,306	21
2099	22,492	60,579	2,232	83,661	13

Table C. 1 (continued).

Year	Mean 60 years	+15% mean	-15% mean	+30% mean	-30% mean
2100	19,557	56,595	1,718	81,760	8
2101	16,901	52,633	1,311	79,621	5
2102	14,517	48,725	991	77,263	3
2103	12,392	44,901	743	74,709	2
2104	10,514	41,188	552	71,982	1
2105	8,865	37,607	407	69,106	1
2106	7,428	34,178	297	66,073	0
2107	6,185	30,919	215	62,983	0
2108	5,118	27,841	154	59,821	0
2109	4,209	24,952	110	56,611	0
2110	3,440	22,259	77	53,380	0
2111	2,793	19,764	54	50,149	0
2112	2,254	17,466	37	46,943	0
2113	1,807	15,362	26	43,780	0
2114	1,440	13,448	17	40,682	0
2115	1,140	11,717	12	37,658	0
2116	897	10,160	8	34,728	0
2117	701	8,769	5	31,917	0
2118	544	7,531	3	29,211	0
2119	420	6,437	2	26,637	0
2120	322	5,476	1	24,196	0
2121	245	4,635	1	21,881	0
2122	186	3,906	1	19,737	0
2123	140	3,275	0	17,725	0
2124	104	2,729	0	15,790	0
2125	77	2,266	0	14,063	0
2126	57	1,872	0	12,489	0
2127	42	1,539	0	11,025	0
2128	30	1,258	0	9,696	0
2129	22	1,022	0	8,459	0
2130	16	824	0	7,299	0
2131	11	665	0	6,371	0
2132	8	532	0	5,485	0
2133	6	421	0	4,664	0
2134	4	329	0	3,886	0
2135	3	256	0	3,232	0
2136	2	195	0	2,608	0
2137	1	147	0	2,089	0
2138	1	110	0	1,673	0
2139	1	83	0	1,354	0
2140	0	57	0	962	0
2141	0	39	0	694	0
2142	0	27	0	508	0
2143	0	18	0	362	0
2144	0	7	0	137	0
2145	0	3	0	55	0