Introducing a circular construction hub for building material circularity in city:

A case study in Leiden, the Netherlands

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Abstract

The Dutch government has published the circular economy goal, which aims to reduce 50% consumption of raw materials by 2030 and realize full circularity by 2050. The goal leads the promotion of the sustainability development, particularly, on improving the resilience of the self-sufficient material supply chain in the Dutch economy. As one of the largest raw material consumers, the construction sector has urgent demand on the solution towards building circularity, which mainly indicates as increasing the use of secondary materials, and reducing the demolition and construction waste. Accordingly, the municipality of Leiden takes the leading role of circular transition, and seeks for the practical solution in construction sector at the local scale.

The circular construction hub is brought out as an effective solution to the building material circularity transition. A series conceptual development and a few pilot projects in Utrecht and Amsterdam were established, the effectiveness is proved by the promising results of transportation reduction, and recycling rate improvement.

Regardless numbers of the studies on the building material flow analysis and the development of the hubs in various forms, limited discussion of practical information for local hubs' development is provided, and little quantitative analysis of the implementation of the circular construction hub was conducted. Decision making for the intermediate steps in the transition towards building material circularity, therefore, has little referencing information.

Hence, this research proposes the main research question as: **How will the circular construction hub support the transition of building material circularity in the cities of the Netherlands?** In order to explore the formation and the influence of the circular construction hub in city with the case study of Leiden. The research firstly specifies the formation of the hub by desk research; then quantifies the urban mining potential and handling capacity of the hub by Material Flow Analysis (MFA); then the suitability analysis of the hub's location is provided by the Geographical Information System (GIS) based on the transportation emission (CO_2 eq kg).

The research aims to draw a comprehensive understanding on the metabolic characteristics of building material flows with implementation of the circular construction hub, and provide a referencing value for municipality's decision making on developing the hub in city Leiden, and further development in the cities of the Netherlands.

Keywords: Dutch circular economy goals, building material circularity, the circular construction hub

Table of Content

Abbreviations

CE Goal: Circular Economy Goal

GHGs: Green House Gases

CDW: Construction and Demolition Waste

UM: Urban Mining

LCA: Life Cycle Assessment

MFA: Material Flow Analysis

GIS: Geographical Information System

MI: Material Intensity

Avg: Average

Eol: End of Life

1. Introduction

This chapter introduces the overarching research background under the context of the Dutch circular economy development in the construction sector, coinciding with the hotspot objectives in Industrial Ecology, which focuses on the improvement of the building material circularity, as well as the mitigation of the climate change (carbon emission). Then, the theoretical framework based on the core concept of circular economy and strategies, circular logistics is demonstrated based on the literature review, followed with the emergence of construction hubs as a comprehensive solution in the transition phase, and concluded by the knowledge. Meanwhile, the case study is formulated on circularity ambition from the municipality of Leiden, which expects to use sustainable building materials and reduce the carbon emission in the future construction plans until 2030. In the end, the research goal and questions are proposed, and the research design is outlined for the full report.

1.1. Background

The Dutch government has established the Circular Economy development goal (CE goal in the following) in 2016 to lead the solutions to mitigate the resource depletion, which called for 50% reduction of primary raw material consumption by 2030, and to achieve 100% circularity, in other words, a waste free economy by 2050 (Government of the Netherlands, 2016). The reduction of primary raw material consumption is expected to be realized by reducing the amount, being replaced by the inexhaustible materials, and more importantly, increasing the share of the secondary material in the total consumption. In addition, the Dutch CE goal also aims to address the climate change mitigation by encouraging the actions of reduction of Green House Gases (GHGs in the following) emission among all the industries. The goal had been responded by the stakeholders in different sectors, especially the construction sector.

In the Dutch economy, the construction sector accounts for 50% of the total raw material consumption (Grondstoffenakkoord, 2018; Vincent Gruis, 2022). Therefore, the construction sector is highly addressed to make circular transition, in terms of the material efficiency. The main objects in the construction sector are identified as the Built Environment (CIRCLE Economy & Metabolic, 2022), which include the residential buildings, the non-residential buildings, and the infrastructures. As a country with high population density, the growing number of people impedes the housing crisis, along with the increasing needs of the infrastructures, as predicted, 75,000 new homes need to be built each year by 2025 at least (CIRCLE Economy & Metabolic, 2022). The large number of the construction demand leads to a massive number of raw materials, as well as the Construction and Demolition Waste (CDW in the following) during the construction and demolition activities. Currently, about 95% of CDW (Schut et al., 2015) is collected for recycling, and ends up with 88% recycling rate in total (CIRCLE Economy & Metabolic, 2022; Metabolic, 2020)Statistically, the recycling rate may look proud, however, by 2016, only 3% of the CDW (Schut et al., 2015) can be returned as secondary material, and the number only grows to 8% by 2022 (CIRCLE Economy & Metabolic, 2022; Metabolic, 2020). The majority of the CDW, such as concrete, bricks and glass, are downcycled and served as the "backfills" for the infrastructures in civil engineering (Schut et al., 2015). Despite of the growing demands of the infrastructures, the needs of the "backfills" cannot cover the size of CDW. Due to the low requirement of the material properties, the existing "backfills" can be 100% reused infinitely (Schut et al., 2015), and its life span is about 80 to 100 years and even longer (CIRCLE Economy & Metabolic, 2022). Therefore, the fresh need for the input will decrease, while the growing demand of construction indicates the increasing volume of CDW, the space to place CDW in "backfill" is saturating, and the remaining value of the material is also buried in the road-base. Hence, the current solution to the CDW flow cannot be identified as a material-efficient method, nor with the circular or sustainable value, and the increasing CDW is becoming an inevitable problem.

In the conventional CDW management system, generating secondary material from CDW has less competitive market value than the primary material, as the transportation distance takes large proportion of the total cost, and it is difficult to make estimation in advance, which could make the secondary material more expensive than the primary option (AT Osborne, 2022). However, due to the post-pandemic strike and increasing geopolitical issues, the uncertainty of the supply chain increases the difficulty of the primary material supply, which leads to the setbacks and even interruption of the construction activities, and results in the increasing cost of the projects (AT Osborne, 2022; Vincent Gruis, 2022). The situation encouraged the stakeholders to explore the potential of the secondary material, which could help to stabilize the material supply with affordable cost by the input of the secondary resources, meanwhile increase the supply chain resilience by localizing the network (Schut et al., 2015). Therefore, increasing the market share of secondary material not only contributes to the material efficiency and CDW reduction, but also is urged by the current economy situation of the construction sector.

Meanwhile, the construction sector is also responsible for 35% of the total CO_2 emission in the Netherlands (Grondstoffenakkoord, 2018; Vincent Gruis, 2022). Under the context of the climate change mitigation, low / zero emission is necessity for the improvement of CDW management system. Construction logistics accounts for more than 30% of the total emission of urban freight transportation (Luik et al., 2021), to implement waste regeneration for secondary material, suitable logistics planning plays an important role on the improvement of transportation efficiency, which helps to largely reduce the cost by shortening the construction time, and is closely related to the reduction of traffic load, carbon emissions and environmental nuisance (TNO, 2022). A logistics planning with considerate spatial and temporal strategy could help to coordinate the secondary supply and construction demand, which contributes to the material circularity.

Therefore, to incorporate the Dutch CE goals, the Dutch construction sector is expecting a comprehensive solution to increase the using rate of the secondary material, which is possibly realized by considering the effective logistics planning with low carbon emission.

1.2. Theoretical framework

1.2.1. Circular economy in the construction sector

- **Concept**

The conventional linear economy model is interpreted as the "take – make- waste" principles (van Buren et al., 2016). With the growing pressure of the environmental degradation, resource depletion and growing demands of consumptions, the linear paradigm is urged to be transitioned due to the little material efficiency and huge environmental impact (Norouzi et al., 2021). The urgency is also indicated by the construction sector.

In the contrast to the linear economy, the circular economy, was considered as a business model that fits the expectation of the metabolism between material and waste in the construction sector (Tirado et al., 2022). The terminology was firstly brought out in the book "(Kneese, 1988)", and further developed by many researchers. One of the good demonstrations of its concept was established by Ellen MacArthur Foundation in year 2012 and updated in 2016 (Ellen MacArthur Foundation, 2016), which emphasizes three basic principles: 1) Eliminate waste and pollution, 2) circulate products and materials (at their highest value), 3) regenerate nature. the concept can be well-illustrated by the famous butterfly diagram shown in **Figure 1** below:

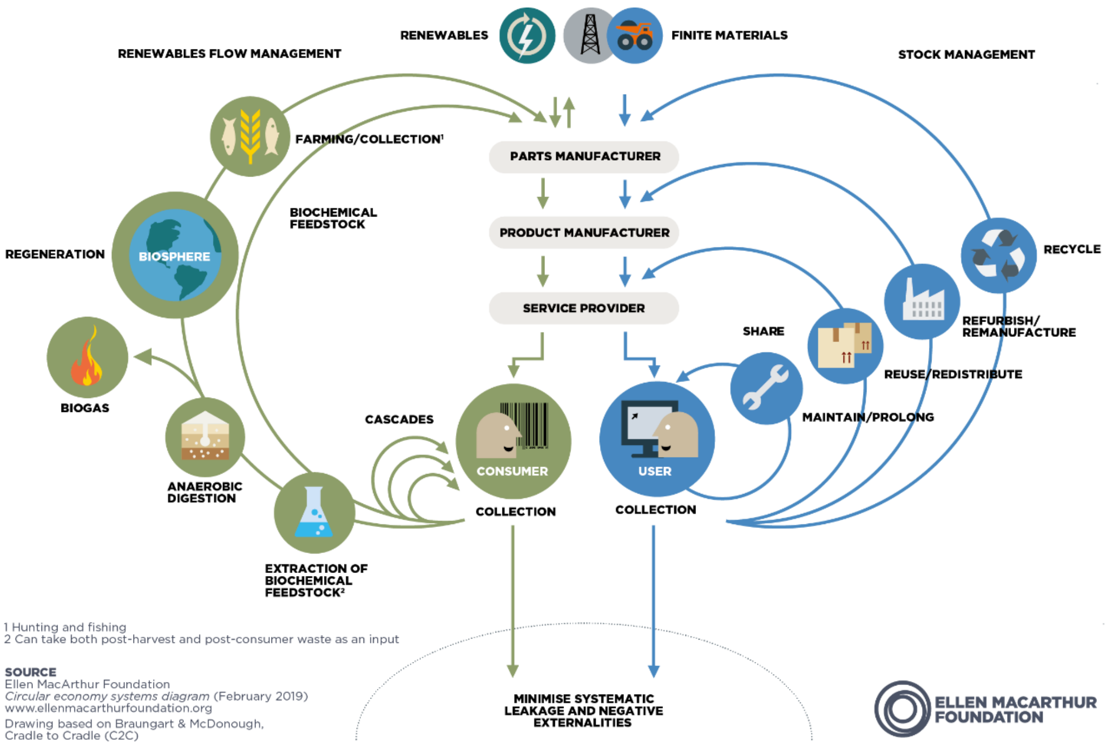

Figure 1 The butterfly diagram demonstrates circular economy (Ellen MacArthur Foundation, 2019)

The butterfly diagram entails the pattern of material flows in a circular economy (Ellen MacArthur Foundation, 2019). The circulation can be concluded by two main cycles, the biological cycle, which shows the circulation of nutrient flows that is carried by biodegradable materials, realized by regeneration of nature. The second cycle, the technical cycle, demonstrates the circulation of product and materials through a series of industrial processes, such as reusing, repairing, remanufacturing, recycling and maintaining. The technical cycle provides instructional value for developing the circular strategies for the building material products.

- **Circular strategies**

In accordance with the technical cycle of the circular economy, the waste hierarchy was established to address the priorities of circular strategies based on their levels of circularity. The "10 Rs" of the waste hierarchy (Potting et al., 2017) is demonstrated in **Figure 2** below.

The most recent waste hierarchy scheme was brought out by the report "Circular economy: Measuring innovation in the product chain": (Potting et al., 2017), which introduces the "10Rs" of circular strategies within the production chain. The "10Rs" represent for "Refuse", "Rethink", "Reduce", "Reuse", "Repair", "Refurbish", "Remanufacture", "Repurpose", "Recycle", "Recover" respectively by their circular level, the strategy with

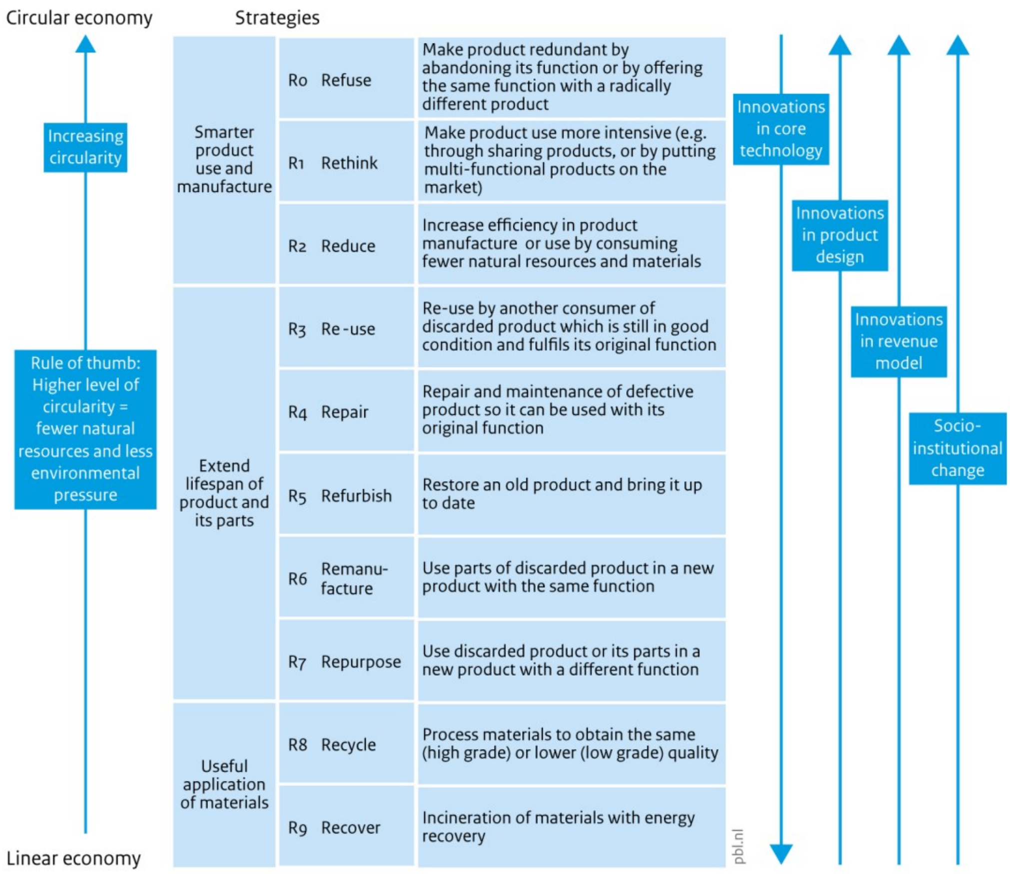

Figure 2 Circularity strategies within the production chain, in order of priority (Potting et al., 2017)

fewer natural resources and less environmental impacts are considered to have higher circular level, the waste hierarchy scheme aims to encourage the stakeholders to the prioritize the strategy by their circular level when taking circular interventions. Similarly, this descending order also represents the level of innovations that is required by product design, the revenue and socio-institutional change of each strategy, while the level of innovations in core technology is demanded reversely by circular strategy.

To begin with, “R0 – Refuse”, means to refuse the redundant functions or product itself by alternatives. “R1 – Rethink”, means to rethink the current product and service scheme, in order to help product to be used more intensively. And “R2 - Reduce” means to reduce the use of product and material by increasing the efficiency of product manufacture and material use (Potting et al., 2017). “R0” to “R2” listed the circular strategies in the early design and manufacture stage, aim to decrease the consumption of natural resources and materials applied in a product chain by less product being needed for delivering a same function, showing the core concept and ultimate goals in the circular economy, while radical progress of technology and innovations are required to implement the first three strategies.

The circular strategies listed from “R3” to “R7” state how to extend the lifespan of the product. “R3 – Reuse” represents for using the product for its original functions again at the end of its previous lifetime. “R4 – Repair”, means to maintain the functionality of the product by fixing the deficient product. “R5 – Refurbish” is to keep the functionality of the product up to date by proper maintenance. “R6 – Remanufacture” means to compose the useful parts from discarded product with its original functionalities. “R7 – Repurpose” is to use the product with different functions when the current functionality is defective (Potting et al., 2017). Extending the lifetime of the product is mostly discussed by stakeholders under the current circumstances, as the value of the product (in terms of its functionality and market value) can be largely preserved with applicable technological, economic and societal interventions.

“R8” and “R9” discuss the circular value from the material perspective of the product, showing the fundamental ways to exhaust the value of materials in a circular way. Of which, “R8- Recycle” means to produce the material from the waste with high quality (upcycle) or low quality (downcycle). “R9 – Recover” is to gain the energy from the material by incineration (Potting et al., 2017). “R8” and “R9” show the useful application of materials when the functionality cannot be achieved in the form of product, hence, limited value can be maintained. These two circular strategies have already been commonly applied by the Dutch economy, solutions with higher circular value are expected. Therefore, in order to solve the problem of waste flows in the construction sector, it is important to implement the “R strategies” at the higher level as possible (Potting et al., 2017; C. Zhang et al., 2022).

Meanwhile, the policy report of PBL 2018 (PBL, 2018) brought out the corresponding “R Ladder” (**Figure 3**) to show the circular strategies in different phases of a product lifetime, the “R Ladder” categorizes the “R Strategies” in different loops. “Narrow the loop” is realized by “Refuse”, “Rethink” and “Reduce” the material consumptions, in order to reduce the material consumption from the root. “Slow the loop” is achieved by “Reuse”, “Repair” and “Refurbish” the products, which aims to extend the lifespan of the product and reduce the material elimination rate. “Close the loop” is performed by “Recycle”, which makes the waste into product to increase the material efficiency. And “Recover” helps to exhaust the material value by energy recovery. The strategies also suggest substituting the products with more sustainable materials.

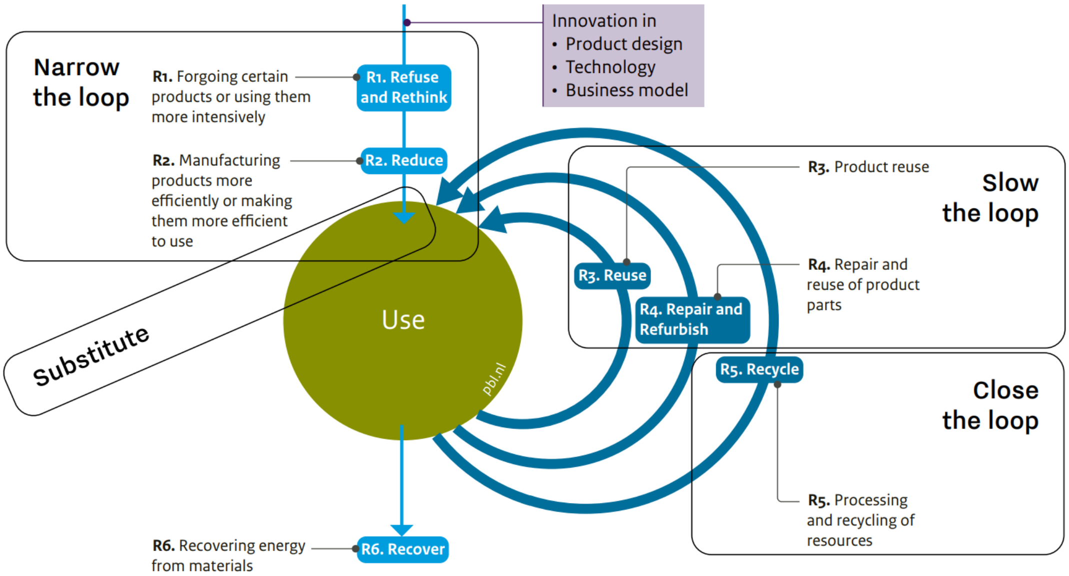

Figure 3 R Ladder and circular economy strategies, (PBL, 2018; Vincent Gruis, 2022)

- ## Urban mining

With the growing attention on improving the material efficiency, Urban Mining (UM) is gradually adapted by the construction sector as an effective way to develop the reliable supply chain (Metabolic, 2022b), and a circular strategy to eliminate waste and reduce the environmental impact (Koutamanis et al., 2018). With the fast development of the construction sector, a large amount of building materials is accumulated in the existing buildings, which can be considered as the stock for material and products, and is identified as urban mines (Mohammadiziazi & Bilec, 2022, 2023).

The resources of the urban mine have two types: one is from the building stocks, the other is from the building material flows (Cossu & Williams, 2015). The amount of the building stocks changes little annually, yet the volume of material flows varies from year to year, depending on the economy, technology and local urban plans (Cossu & Williams, 2015). In this sense, the former (stocks) is considered to have more characters as "mines", and the latter (flows) shows the supplementary value in quantifying the potential of "mines". The secondary material can be produced from both sources (Koutamanis et al., 2018).

Further, the resource extracted of the urban mining can be identified with different levels of the integration of functional and technical life cycle of building materials. According to the model "Hierarchy of material levels in building" (Elma Durmisevic, 2006) in **Figure 4**, 4 physical levels of buildings are identified: 1) System level, represents the composition of components that perform the system functions (such as bearing, finishing, insulation, reflecting, distributing); 2) Sub-system level, represents the compositions of components that carry the lower level of the system functions; 3) Component level, represents the lowest level of functions that can be carried by material and elements in the building assembly (such as windows, stairs, doors); 4) Material level, represents the lowest level that can be decomposed in the buildings.

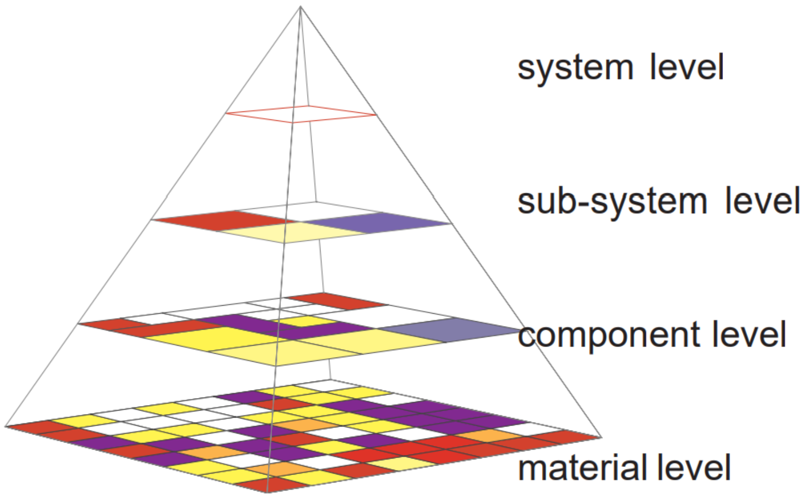

Figure 4 Hierarchy of material levels in buildings, (Elma Durmisevic, 2006)

With current technologies, urban mining can be established on the component level and the material level to produce secondary products and materials, explorations at the sub-system level (such as façade) are under-developing (Hanemaaijer et al., 2021). Urban mining corresponds to the circular strategies of "Slow the loop", which helps extends the lifetime of building components, products and materials by reusing, repairing, refurbishing, remanufacturing and repurposing (such as reusing the building components and materials, and repurposing the building materials in the new construction projects or furniture design) (Metabolic, 2022b; New Horizon, 2022). Meanwhile, "Close the loop" is also addressed by recycling the CDW for secondary materials in urban mining (Hanemaaijer et al., 2021; New

Horizon, 2022).

Therefore, urban mining is one of the good employments on performing the circular strategies for the development of the circular construction sector. In this sense, CDW flows can be efficiently reduces, the secondary resource (in terms of components, products and materials) can be extracted, which aligns with the expectations of the municipality of Leiden and the building circularity.

1.2.2. Circular logistics in city

From the same report "Circular economy: Measuring innovation in the product chain": (Potting et al., 2017), the circular strategies and their corresponding roles in product chain are demonstrated in the **Figure 5** below.

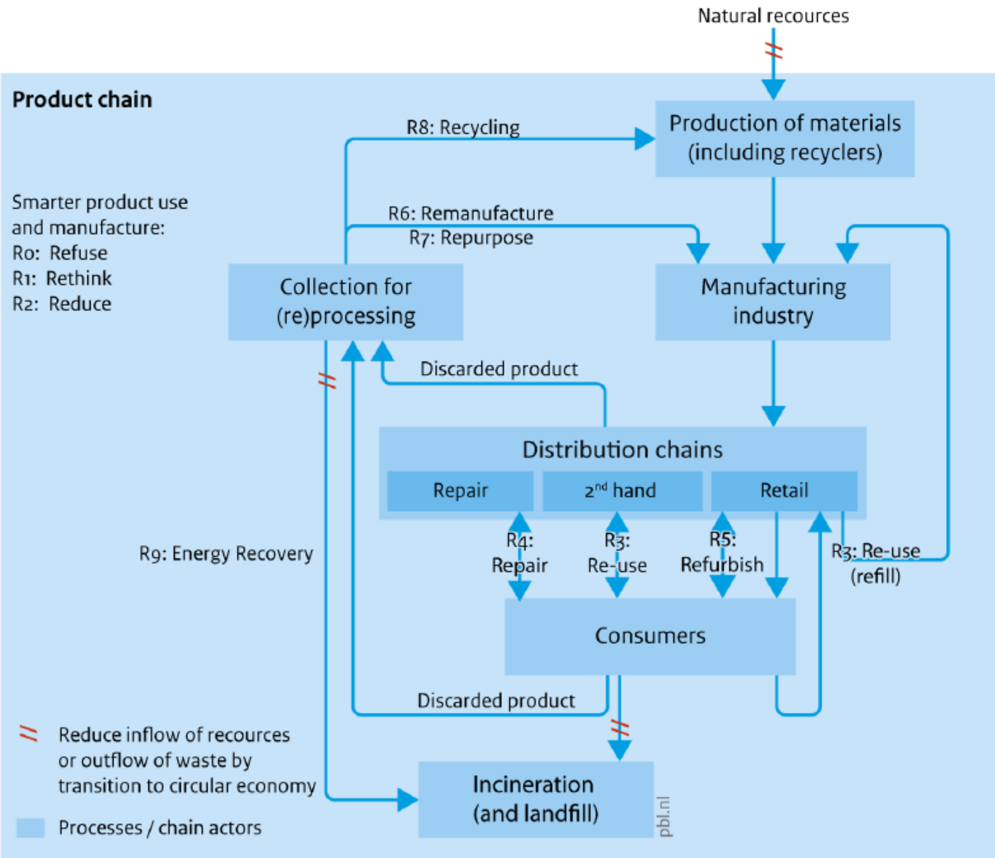

Figure 5 Circular strategies and their role of actors within the product chain, (Potting et al., 2017)

In the production chain, the processes/ chain actors that are related to the urban mining are mainly addressed by collection and distribution chains, which could help to realize slowing the loop by "Re-use, Refurbish, Repair" among consumers. While, other circular strategies, such as "Remanufacture" and "Repurposes", require further steps in the product chain by manufacturing industry, and "Recycling" by production industry. Therefore, the coordination among actors and processes connects the activities in the production chain, plays an important role on realizing the circular strategies.

Hence, under the circular context, the supply chain does not only focus on forward flows of production delivery from production to consumers, but also provides the reversed flow of goods/wastes from consumers to producers (Dekker et al., 2004). The moving of the goods, planning, executing, and controlling the efficient flow of products, services, and information through an economic system are identified as logistics, of which, the forward flows from production to consumers are Forwards Logistics (FL), and the reverse flows from consumers to producers are Reversed Logistics (RL) (Christopher, 2011; Ding et al., 2023). RL, Green Logistics/ Green Supply Chain Management (GSCM) (Calmon & Graves, 2017; Ding et al., 2023), Closed-Loop Logistics/ Closed- Loop Supply Chain (CLSC) (Stindt & Sahamie, 2014; Mishra et al., 2022) are often discussed coherently in the circular economy development. The concept can be well-summarized as the circular logistics, which refers to the logistical processes that enable value to be captured after a product has been used, in order to benefit new products (Andersson & Söderberg, 2022).

In this sense, the adequate planning of the circular logistics is essential in realizing material circularity in the construction sector. The logistics system in the construction sector is considered to be comprised by two networks, one is the political network, which related to the administrative area (such as municipality), the other is the network one, which has a rather vague system boundary, the system can be identified by the range of material flows, the collaboration among stakeholders etc., both networks are significant under the development of the circular economy (van den Berghe & Verhagen, 2021). Usually, the political network is adopted as the system boundary in the initial stage for the transition, while in practice, material flows distribution play more essential roles. The spatial distribution determines the routes and the loads of transportation, which cause the GHG emissions and environmental nuisances; the transportation influences the delivery time, and the match between supply and demand. Therefore, the spatial characters are addressed by developing circular logistics for CDW management in the construction sector. (Dekker et al., 2004; Göswein et al., 2018; Luik et al., 2021; Mishra et al., 2022; Ding et al., 2023).

- **Spatial analysis – GHG emission of Transportation**

Transportation and relevant infrastructures need to be developed for the reuse of excavated waste and by-products (Hale et al., 2021), certain logistics considerations about the allocation of vehicles and materials are vital for implementing the RL flows, which determines the decision making on the circular strategies by stakeholders (Ambekar et al., 2022). Meanwhile, site selection of waste treatment plans and storage significantly influence the RL in network perspective in the CDW management, various factors should be taken into consideration for the decision making (Chileshe et al., 2018; Ding et al., 2023).

Conventionally, the central aim of the construction logistics is to ensure the timely deliveries (Andersson & Söderberg, 2022), in order to operate the successful construction processes on time within the budget (Dixit et al., 2022). With the leading of the policy and the increasing environmental awareness, the cost of the building projects is not the only dominance of the decision making, the overall environmental performance and life cycle management of the buildings and materials are also significantly influencing the logistics planning (Chileshe et al., 2018; Ding et al., 2023; Dixit et al., 2022). The GHG emissions related to building materials draws increasing attention due to the requirements of energy transition (Akbarnezhad & Xiao, 2017; Lützkendorf & Balouktsi, 2022). In each process of the construction (demolition) project, the Embodied Energy (EE) is directly consumed in construction, transportation, fabrication, and administration, and has great relevance to building materials, assemblies, and equipment (Dixit, 2017; Dixit et al., 2022). Moreover, as building materials are usually of bulky volumes with low market value, the transportation of the building materials takes the most share of GHG emissions and the total cost, as well as the inner-city traffic irritations and environmental nuisance (Chileshe et al., 2018; Göswein et al., 2018; Dixit et al., 2022; Tsui et al., 2022a).

In this sense, the transportation efficiency and the location where materials are processed decide the overall traffic conditions and environmental performance during the construction / demolition activities. The spatial analysis for transportation and material processing sies draw great importance in the development of circular logistics and the circular construction sector. In which, the GHG emission is often used as the dominant indicator for evaluating the environmental performance, and GHG emissions is usually equivalent to the carbon emission in the quantification. Life Cycle Assessment (LCA), Material Flow Analysis (MFA) Geographical Information System (GIS) are combined in different forms for the quantitative studies, in order to draw a comprehensive understanding of material distribution and GHG emission with spatial characters (Ding et al., 2023). Other factors, such as the installer skill, technology/equipment, prefabrication, planning and forecasting, company culture, site condition, material movement, material packaging, superintendent experience, on-site waste system, government regulations, weather conditions, and finished material protection are also important factors to be considered for logistics planning in helping to minimize the construction waste. Meanwhile, material damage, rework requirement, and construction waste quantity influence the site of the logistics facility as well (Dixit et al., 2022).

The activities in the construction sector are highly depended on the material supply chain, and coordinated by the logistics system, which is limited by the physical flow network, and influenced by the virtual collaboration network (van den Berghe & Verhagen, 2021). The location of the projects and relevant geographical information are essentials on studying how to optimize the construction sector in the transition towards circularity(Furlan et al., 2020; Tsui et al., 2022b; Yeow & Cheah, 2019). At the beginning of the transition, the physical flows, in terms of material flows, waste flows and the logistics flows are largely discussed by the academies, policy makers and businesses, they aim to develop efficiency on flow distributions and exchanging in a more practical way.

Therefore, the theoretical framework (**Figure 6** below) is built upon the core concept of circular economy in the construction sector, and further developed by the circular strategies of "10Rs". Then the circular solution in the research focuses on the strategies that address "slow the loop" and "close the loop" in the production chain, and implements with the concept of urban mine and circular logistics.

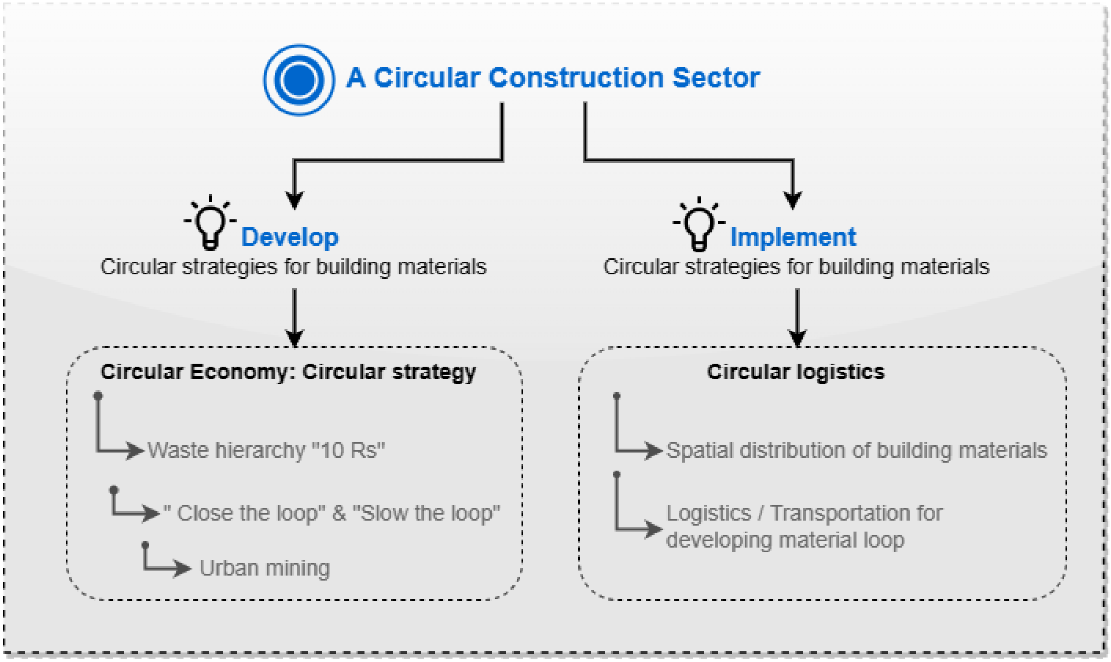

Figure 6 The theoretical framework of the research

1.2.3 Knowledge gap

Many studies were investigated to explore the possibilities of realizing building material circularity by increasing the secondary material use, of which, policy advice (Schut et al., 2015; Grondstoffenakkoord, 2018) and strategic instructions (Potting et al., 2017) were given, technologies for building material recycling and secondary application are developing (Gálvez-Martos et al., 2020, 2018; Taelman et al., 2020; van den Berghe & Verhagen, 2021; Y. Zhang et al., 2015). In addition, the quantitative estimations were given to evaluate the urban mining potential between demolition waste and construction demand of the building stocks, of which, the study from (Yang et al., 2022) quantifies the urban miming potential under the Dutch national level until year 2050, and the study of (Verhagen et al., 2021) calculates the matching relation in city Leiden until 2030. Both research showed that, quantitatively, the demolition waste cannot satisfy the demands of future constructions either by 2030, or by 2050, primary materials are always needed. The studies bring out a rather frustrating fact that, the Dutch CE goal may be failed by secondary material circulation. However, the results do not mean that the circular transition agenda should be interrupted, on the contrary, they indicate that the building material circularity improvement has great growing potential, yet limited studies were given for the intermediate transition process in the short term, and with practical value.

In this sense, the comprehensive solution to the circular construction sector is required to initiate the material circularity. From the studies of (Verhagen et al., 2021; Yang et al., 2022), to mitigate the gap of material circularity, the solution needs to reduce the mismatch between demolition waste and construction demand from 3 perspectives: 1) The structural mismatch of material types and properties. As the old building materials from demolition may not be needed by the new constructions. 2) The temporal mismatch between demolition and construction. As the lifetime of the building can last for decades, and the operation time of demolition or construction can also last for months and years, many factors can influence the progress of the project (such as collaboration, municipality's planning, finance, labour force etc.), which brings a lot of difficulties to the coordination between demolition supply and construction demands. 3) The spatial mismatch between demolition and construction projects. As transportation consists of the majority of the cost in the secondary material value chain, it is less attractive for contractors to spare extra attention on waste management with longer traveling distance.

To align the demolition waste and construction demands, the coordination of supply chain and its logistics plays a significant role. Therefore, many studies made the investigations and concluded with a term called "The construction hub". The construction hub has various interpretations, which could help mitigate the material mismatch by increasing the reusing rate of the material, reduce the time mismatch by providing secondary material storage, and improve the spatial connection by logistical planning (Anna, 2021; Luik et al., 2021; Metabolic, 2022a; Versnellen, 2022). These studies bring a lot of insight on practicing the circular strategies in the construction sector. However, as each construction/demolition project has different scales of networks, in terms of supply chain, stakeholders and logistical planning (Ding et al., 2023), the implementation of the construction hub needs to be discussed with a case-specific study. The formation of the hub and its influence on the building material circularity need to be analysed for decision making in the future development of the construction sector.

Therefore, this research aims to fill some knowledge gaps on the development of construction hubs as an intermediate solution in the transition towards building material circularity. Relevantly, a case study of Leiden with the latest database if referenced to entail the construction hub, in terms of its scale, functionality, quantitative performance and site selection.

1.3. Leiden case study specification

As limited time is left for the first milestone of Dutch CE goal by 2030, urgent and practical interventions are required. The city of Leiden is equipped with sufficient conditions to demonstrate an exploratory case study for developing the solution to the circular built environment.

The city and the municipality of Leiden plays a leading role of the circular transition nationally, which builds up a good position for the development of circular solution. Close conversations were arranged between the municipality and the institutions to conduct further research on the solutions. The circular ambition is interpreted by 4 pillars: 1) socially responsible procurement, 2) circular construction, 3) valorisation of material flows, and 4) learning and communicating, in which, circular construction is highly addressed (Frouke Pieters, the circular project manager of Municipality of Leiden, interview, May 17th, 2022).

By the year of 2030, 8,800 homes and 2,700 student rooms are planned to be built, a series of demolition and renovation are scheduled accordingly (Municipality of Leiden, 2022). Therefore, a large amount of building materials will be demanded by the constructions, meanwhile, huge CDW flows can be expected through demolition. The municipality of Leiden would like to promote the circular construction by increase the secondary material use, and reduce the carbon emission among the construction and demolition activities. (Frouke Pieters, the circular project manager of Municipality of Leiden, interview, May 17th, 2022).

The city Leiden demonstrates the similar consumption pattern as national economy, of which, the primary material dominants the total material consumption in the construction sector, little secondary material is used, limited circularity can be witnessed in the current built environment in Leiden. Accordingly, large amount of CDW needs to be reduced and eliminated in a circular way.

Additionally, the Dutch economy shows high dependency of the global supply chain, 68% of the resource is imported (van Buren et al., 2016), and so does the city Leiden. With the extinguished characters of history and culture, little industry and factories are located in Leiden. Therefore, the building material supply and waste material management are highly dependent on the national logistics and supply chain. As showing in the **Figure 7** (Luik et al., 2021), the major building materials used by Leiden are transported from different regions in the whole Netherlands, localize the supply chain could bring the positive impact on the material efficiency. Therefore, effective solution to coordinate the local supply chain is expected by logistics planning.

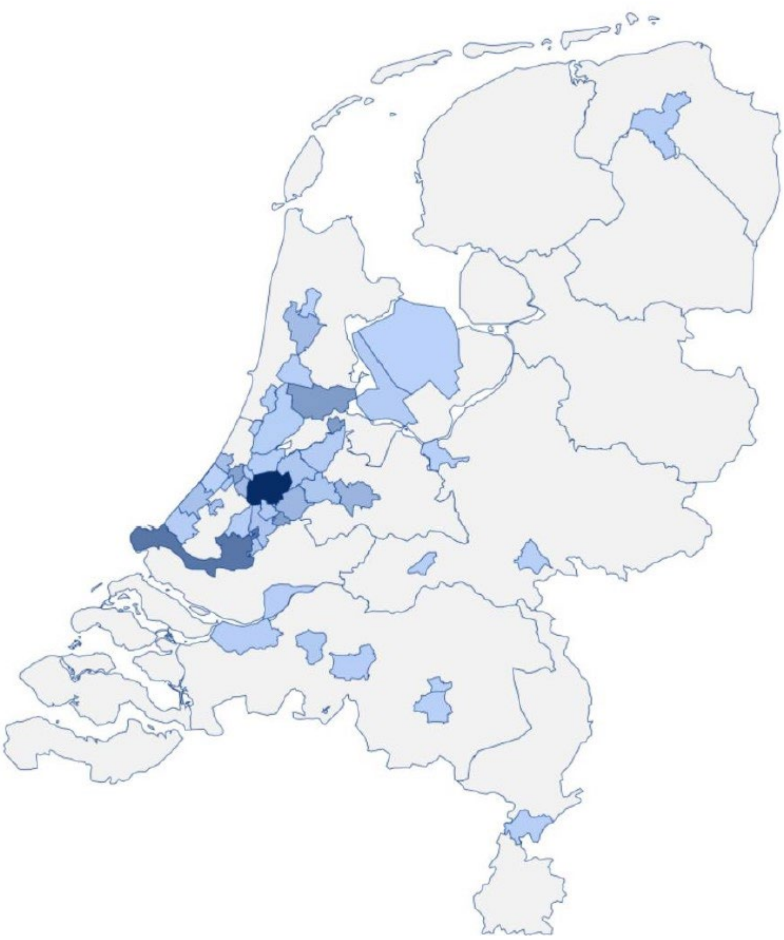

Figure 7 Building material Origins, Leiden

(With the exception of stone, sand, soil, measured by weight) (Luik et al., 2021)

Meanwhile, due to the protection of the cultural and historical value, Leiden keeps the old streets and roads, results in a compact layout of the city. Inner-city transportation for demolition and construction activities brings a lot of pressure on traffic, which results in high carbon emission and environmental nuisance. The compact city layout also brings difficulties to coordinate heavy transportation, parking, and on-site material storage, which delay the building activities (Luik et al., 2021), efficient logistics planning is highly demanded.

1.4. Research questions

This research aims to explore the formation of the circular construction hub and the material efficiency performance of implementing the hub in the city Leiden. In order to provide constructive evidence on assisting the decision making for the municipality, and future development of the circular construction hub at the city scale in the Netherlands. As the outcome of the research, the embodiment of the circular construction hub in Leiden, the quantitative analysis on the building material stocks and the urban miming potential of building materials, the capacity and location of the circular construction hub are investigated. And recommendations for future development will be provided.

The main research question is formulated as:

How will the circular construction hub support the transition of building material circularity for the cities in the Netherlands?

To draw a further analysis on the case study, the sub-research questions are formulated as:

- How to specify the circular construction hub in the case study of Leiden?
- What are the historical (2012-2021) and future (2022-2030) urban mining potentials between demolition waste and construction demand in Leiden?
- What is the capacity of the proposed circular construction hub based on the future construction plans in Leiden?
- Where is suitable location of the circular construction hub based on the evaluation of transportation emission?

1.5. Research design

The report consists of six chapters, the first chapter introduces the overall background, problem statement, literature review and the research questions. The second chapter introduces the research methods. The third chapter demonstrates the results of the circular construction hub and its performance. The fourth chapter provides the discussion and interpretation of the results. The fifth chapter presents the limitations of the research and the recommendations for the future study. Then the report ends up with the overall conclusion in the sixth chapter. The research flow diagram is demonstrated in Research Outline the **Figure 8** below：

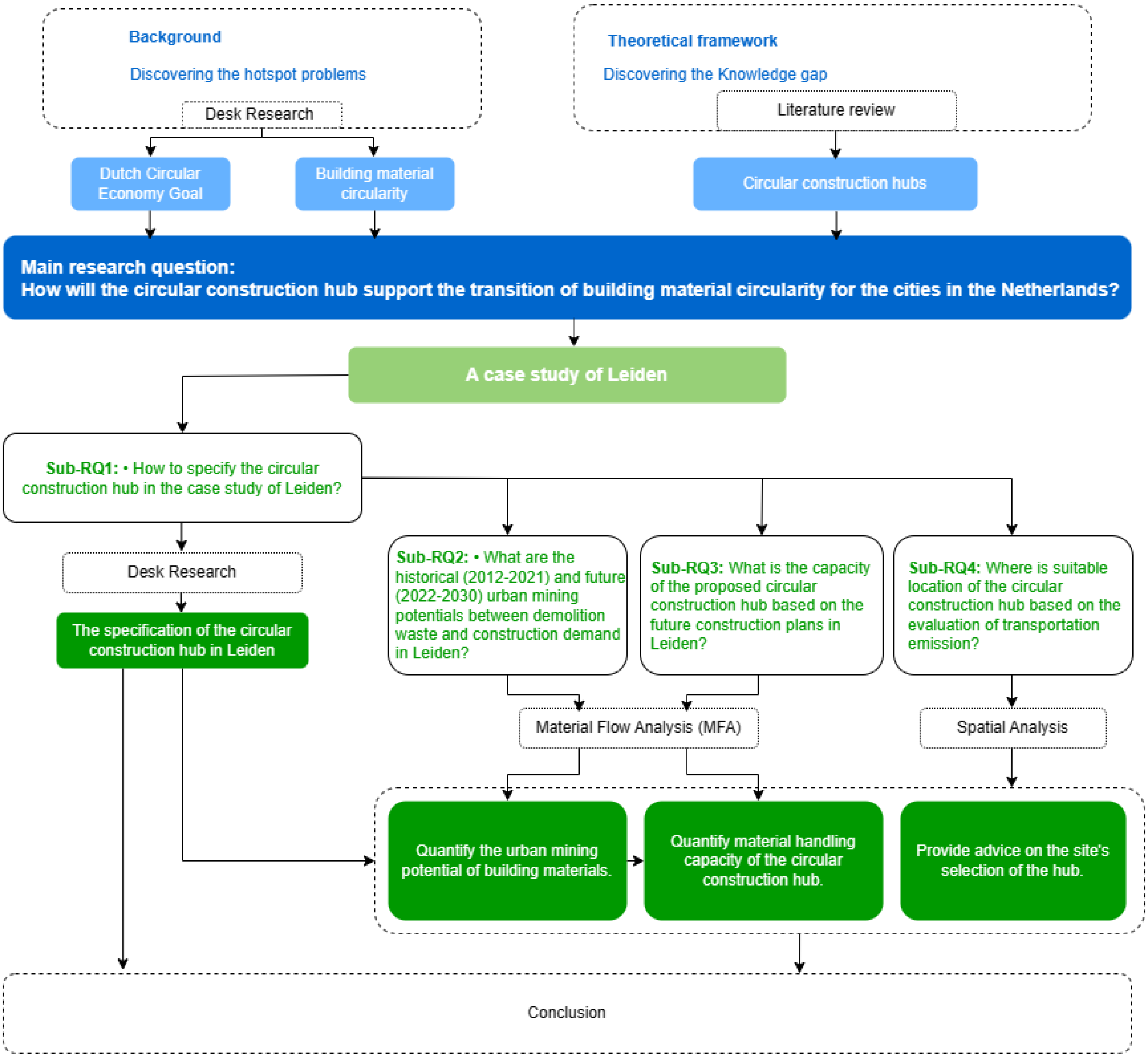

Figure 8 Research flow diagram

2. Research methods

This research explores how to entail the circular construction hub, and its performance of building material efficiency and the site selection in city Leiden. The research methods can be summarized into two ways:

1) **Qualitative research on defining the hub by performing the desk research on previous studies.**
2) **Quantitative research on case study to evaluate the solution of the circular construction hub.**

   Of which, Material Flow Analysis (MFA) is established to calculate the urban mining potential of building materials, and follows with quantification of the capacity of the circular construction hub. Then suitability analysis is employed by Geographical information System (GIS) for site selection of the hub, based on the transportation emission.

2.1. Qualitative research

2.1.1. Step 1: Exploration the Circular construction hub in previous studies.

The institutions and authorities have made efforts on investigating the transition towards circularity in the construction sector. Integrated with the theoretical framework in chapter 2, increasing the secondary material usage is highly depended on the logistical feasibility, hence, applying circular strategies in the construction sector needs the logistical interventions by the coordination of material flows, transportation, storage, material processing and collaboration. In this sense, the comprehensive solutions are developed to meet the requirements by the construction sector. Therefore, the concept of the **construction hub** was brought out, which aims to help improve the logistics planning, increase the material efficiency and reduce environmental footprint during the construction activities (Anna, 2021; Luik et al., 2021; Metabolic, 2022a; New Horizon, 2022; Versnellen, 2022).

The construction hub can be interpreted in different forms under various purposes. The goal of the construction hub is to improve the exchanging flows of goods among stakeholders, which can be realized by these fundamental functionalities in the physical infrastructures: 1) serve as the logistics point outside the city for product distribution and transportation planning; 2) serve as storage for building materials and products in order to align the time difference between supply and demand; 3) serve as collection and trading centre for waste and secondary materials, realizing the material upcycling under the circular context(Anna, 2021; Metabolic, 2022a). Meanwhile, some digital and informational functionalities can also be implemented upon the physical structure, such as the database for material trading, and the digital marketplace for secondary market (Metabolic, 2022a). The physical form of the hub is advised to initialize the development of the construction hub, with the development and expansion of the network, it is always necessary to combine the physical hub with the digital hub, as information sharing is important for stakeholder to make decision.

The concept of the construction hub is still under-developing, as the transition towards the circular construction sector is at the initial stage. A few concepts / the purposes of the hubs are summarized as the typical types of the construction hubs in the previous studies, their characters and functionalities are introduced as follows:

1) **The construction hubs (Or the construction logistics hub)** (Anna, 2021; Metabolic, 2022a)

The construction hub (some called the construction logistics hub (Metabolic, 2022a), or the logistics hub (Luik et al., 2021)) is the best-known type of the hubs, which serves as the logistics point for traffic coordination, building material and product storage and distribution. The construction hub can save the traveling distance and intermediate times of transportation, which helps to reduce the traffic loads, transportation cost and GHG emission with promising amount (Luik et al., 2021; Metabolic, 2022a). However, the construction hub prioritizes the logistics (transportation) efficiency than the circular principles, promotion of the secondary material reusing or recycling are not always addressed by the construction hubs (Metabolic, 2022a). The BouwHub of VolkerVessels in Utrecht (VolkerWessels, 2022), the logistics hub of Versnellen (Versnellen, 2022), and the logistics hub in Schiphol Centrum (Schiphol, 2018) demonstrate good examples of the construction hubs in reduction of traffic and GHG emissions, and improvement of delivery efficiency and collaboration.

2) The storage hub (Metabolic, 2022a)

The storage hub serves as the storage place for secondary materials, because in practice, it is very difficult to schedule the timely reusing or repurposing the secondary materials right after their collection due to the long operational time of each construction/ demolition project (Metabolic, 2022a). The storage hub can fill the time gap of each waiting time and avoid loss of the secondary resources, the circular principles are addressed, but the logistical consideration is less involved. The Materiaalbureau in Amsterdamis an example of the storage hub, materials such as paving stones, benches, playground equipment, streetlamps etc. are stored for secondary use (Gemeente Amsterdam, 2022).

3) The circular construction hub (Anna, 2021; Metabolic, 2022a)

The circular construction hub is the concept that is built upon the construction hub, which not only includes the logistical coordination, but also considers the circular strategies for secondary material collection, processing, upcycling and trading. Therefore, the circular construction hub is more preferable in the future development of circular construction sector. A few pilot projects are established. The Circulaire Bouwhub of Bnext.nl in Utrecht (Bnext.nl, 2021), provides storage and transhipment of used building materials, and enables high-quality reuse of wood released from dismantling by wood workshop, which makes the secondary material circulation easier and more profitable, meanwhile, creates a number of job opportunities for societal well-being. And the Logistic City hub in Amsterdam (ctPark Amsterdam, 2022), which will be completed by the early 2023, are going to be the first XXL city hub in the Netherlands with multiple level of models and functionalities, business activities, from storage and packaging to distribution and transport to high-quality office space.

In the report "Kansen voor circulaire bouwhubs in de Provincie Zuid-Holland" (Opportunities for circular construction hubs in the Province of South Holland) by TNO (Anna, 2021), further specification was given to differentiate the construction hubs and resource hubs by the types of materials. Of which, **the construction hubs** take the non-bulk building materials (such as bricks, woods and glass), while **the resource hubs / raw material hubs** take bulk materials (such as sand, gravel, stones). Additionally, the hubs with definition of "circular" prioritise the circular strategies of promoting the secondary materials, the hubs defined without "circular" dose not emphasize or even not align with the circular principles or secondary material circulation (Anna, 2021). To make a clear demonstration of the functionalities and objectives of different types of hubs, the following matrix in **Figure 9** is given:

<table>
<tr><th></th><th></th><th>Storage hubs</th><th>Construction hubs</th><th>Resource hubs</th><th>Circular construction hubs</th><th>Circular resource/raw material hubs</th></tr>
<tr><td rowspan="6">Functionalities</td><td>Logistical planning</td><td></td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>Distribution of goods</td><td></td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>Material storage</td><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>Collection</td><td></td><td></td><td></td><td>+</td><td>+</td></tr>
<tr><td>Processing and upcycling</td><td></td><td></td><td></td><td>+</td><td>+</td></tr>
<tr><td>Trading</td><td></td><td></td><td></td><td>+</td><td>+</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="4">Objectives</td><td>Primmary bulk materials</td><td></td><td></td><td>+</td><td></td><td></td></tr>
<tr><td>Primmary non-bulk materials</td><td></td><td>+</td><td></td><td></td><td></td></tr>
<tr><td>Secondary bulk materials</td><td rowspan="2">+</td><td></td><td></td><td></td><td>+</td></tr>
<tr><td>Secondary non-bulk materials</td><td></td><td></td><td>+</td><td></td></tr>
</table>

Figure 9 Demonstration of different types of hubs (Integrated with (Anna, 2021))

2.2. Quantitative research

2.2.1. Material Flow Analysis (MFA)

Material Flow Analysis (MFA, in the following) is one of the core methodologies of Industrial Ecology, which quantitatively addresses the rates of material use, material loss, efficiency of recycling and other interesting parameters, in order to provide useful insights for systematic evaluation, industrial engineering opportunities and environmental improvement (Graedel, 2019).

The concepts of MFA can be interpreted diversly based on their conceptual backgrounds, 1) scale of the system (e.g., global, national, regional, neighbourhood etc.), 2) materials investigated (goods and/or substances), 3) databases used (e.g., material flows derived from national or international econometric statistics, physical substance flows measured by specific sampling, and analysis campaigns) (Allesch & Brunner, 2015; Bringezu & Moriguchi, 2019).

MFA activities can be classified into two types: 1) Material flow accounting, 2) Material / substance flow analysis. The previous addresses the statistical activity, which provides the data for the national or regional database, and all types of materials can be included. The later emphasizes the analytical activity, which serves as the reference for decision making for policy makers or institutional research, only one material /substance is concerned each time (Allesch & Brunner, 2015; B. Müller, 2006a; Bringezu & Moriguchi, 2019; Graedel, 2019).

From the temporal perspective, MFA can be generalized by static MFA and dynamic MFA. The former is the fundamental of MFA method, which calculates the material flows and stocks on the yearly basis (Bringezu & Moriguchi, 2019; Graedel, 2019). The latter usually applied to forecast the material flows and stocks dynamic in a long-term with the interplay of the time on the yearly bases, the model can be based on stock-driven (B. Müller, 2006b) or the material flow driven (Fishman et al., 2014).

A complete MFA research should include a clearly defined research system with specified materials or substance; the detailed description of each flow in the system should be given; a clear result should be presented diagrammatically or numerically; and the discussion should be demonstrated (Bringezu & Moriguchi, 2019; Graedel, 2019). Additionally, regardless of the type of the MFA, the calculation follows the main principle of the mass balance, of which, the sum of all the inflows to the system equals to the sum of all the outflows and the changes of the stocks (Bringezu & Moriguchi, 2019).

2.2.1.1. Step 2: Quantification the historical and future urban mining potential of the building materials in Leiden

To begin with, it is important to learn the quantity of the demolition waste, and the material demands for the construction in each year, in order to quantify the matching amount between demolition supply and construction demand in the building stocks. Therefore, in the first step, the building material accounting is employed, the model is a static model built upon the bottom-up manner on the yearly basis.

- **MFA system boundary**

The system is defined as such: the system boundary is scoped by the administrative area powered by the municipality of Leiden. The building materials of bricks, wood and glass are taken into consideration (as the result from the defined system boundary, with the respect of narrative logic, the further discussion of the range of building material flows is specified under Chapter 3.1) and calculated individually. The MFA research covers two periods of time with the respective of the data availability: 1) The historical period is from 2012-2021, 2) The future period is from 2022-2030.

- **The quantity of building materials**

The quantity of the material flows is calculated by the buildings' attributes and their relevant material intensity coefficients (Mohammadiziazi & Bilec, 2022, 2023). In the research, each material is quantified by its surface area and the material intensities of the corresponding building type, the function is presented as follows (Sprecher et al., 2021; Verhagen et al., 2021; Yang et al., 2022):

$$\begin{aligned}\boldsymbol{Material\ quantity\ (tons)} \\ &= \boldsymbol{Material\ Intensity\ based\ on\ buildin\ types\ (kg/m^2)} \\ &* \boldsymbol{Surface\ area\ (m^2) * 0.001}\end{aligned}$$

The building types were generalized by non-residential buildings, which includes offices, commercial and other types of building, as well as residential buildings, which can be divided into row house, single house, high rise, apartment (Sprecher et al., 2021; Verhagen et al., 2021).

The Material Intensity coefficients are referenced from the research of (Sprecher et al., 2021), due to the scattered data information provided from database, and for the convenience and data consistency in the whole research, the each material intensity are considered with the average value in both components and structures, the detailed information is shown in the Table 1 below (Sprecher et al., 2021):

Table 1 Material Intensity (MI) of buildings (Sprecher et al., 2021)

		Average MI in both components and structures		
Building types		Brick (Kg/m2)	Glass (Kg/m2)	Wood (Kg/m2)
Non-residential building	Offices	363.7	15.3	24.3
	Commercial	148.5	3.3	50.2
	Other	317.1	10.5	37.0
Residential Buildings	Row house	124.1	0.0	69.3
	Single	635.3	0.0	246.7
	High Rise	245.8	0.0	61.1
	Apartment	310.3	0.0	49.1

- **The quantity of surface areas**

Due to the inconsistency of the database, different units were recorded for the information of demolition and construction projects, and the building types were identified by different categories then Table 1. Therefore, in order to draw valid conclusion, a few modifications were performed during calculations.

1) For the historical period (2012-2021), the construction quantity references from database "Nieuwbouw Monitor" (Nieuwbouw Monitor, n.d.), and the demolition quantity is sourced from the database of Leiden (Municipality of Leiden, 2022). In two databases, the construction projects were recorded by the surface area, while the demolition projects were recorded by the building units. In order to fulfil the calculation condition, it is necessary to transfer the building units into surface area for demolition projects, due to the lack of data record, a few assumptions were made for unit conversion based on the previous study of (Verhagen et al., 2021). Of which, the surface area corresponding to each building unit is calculated by the following formula, the detailed calculation process is described in the **Appendix I - Historical urban mining potential** calculation:

$$\boldsymbol{The\ surface\ area\ corresponding\ to\ each\ building\ unit}\ \ (\boldsymbol{m^2/unit})$$
$$= \frac{\boldsymbol{The\ total\ residential\ areas\ (or\ non-residential\ areas)}\ (\boldsymbol{m^2})\ \text{(Verhagen et al., 2021)}}{\boldsymbol{total\ residential\ units(or\ non-residential\ units)}\ \text{(Municipality of Leiden, 2022)}}$$

2) For the future period (2022-2030), the construction quantity references from the Municipality of Leiden, the plans is published on the websites of the municipality (Municipality of Leiden, n.d.). Due to the uncertainty of the construction plans, accurate data of construction area cannot be collected yet until the project is fully established, therefore, the surface area of each construction plans was marked and measured manually in the GIS system according to the description of the construction plans, the calculation

map is demonstrated in the **Figure 10** below.

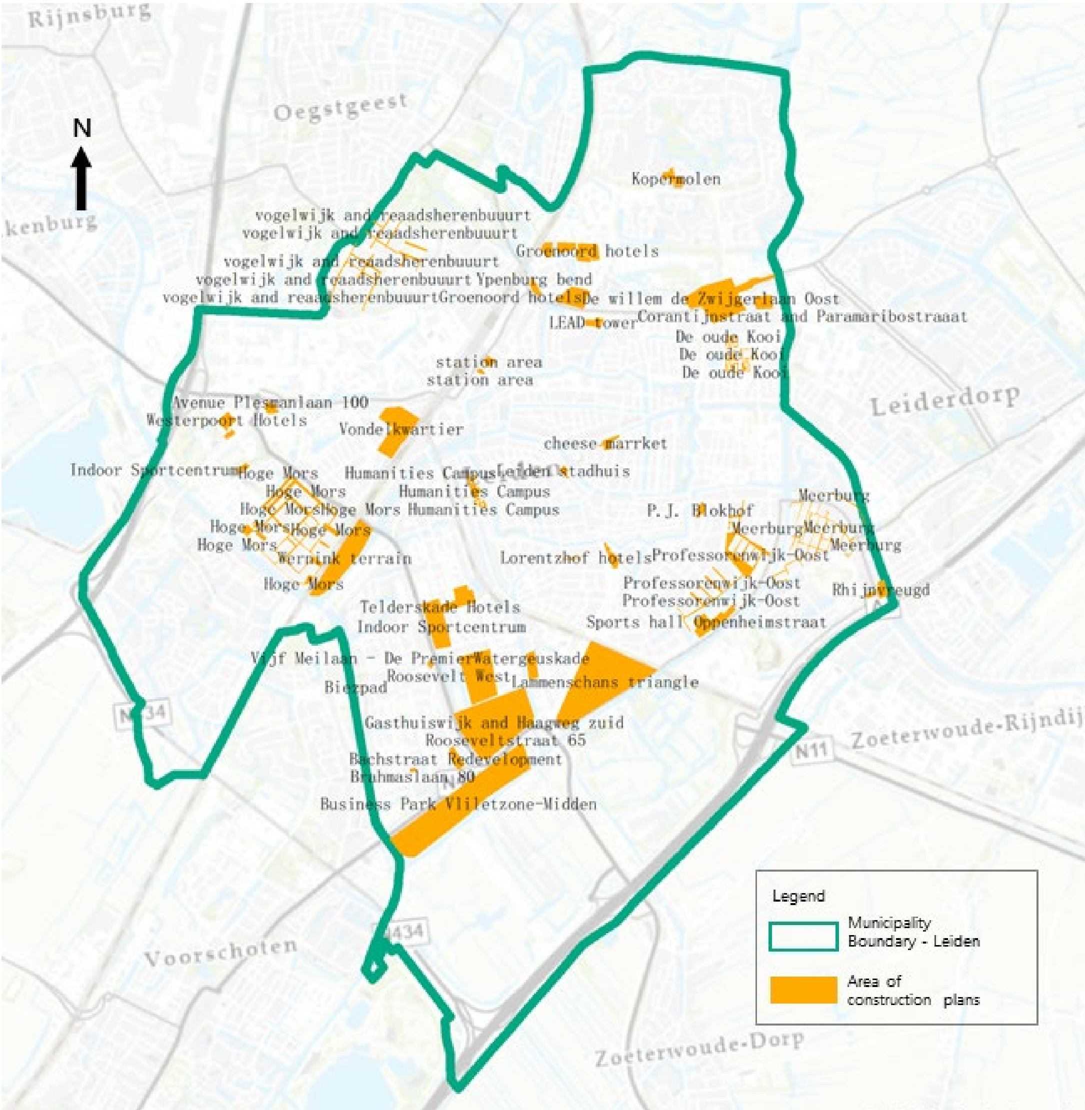

Figure 10 Construction plans in the future years (2022-2030), (Municipality of Leiden, n.d.)

The quantity of future demolition area also lacks source of data, to keep the consistency of the analysis, assumptions of demolition rate of the future years was made based on the previous study of (Verhagen et al., 2021), and the corresponding demolition area each year is calculated by:

$$\boldsymbol{Demolition\ area}\ (\boldsymbol{m^2}) = \boldsymbol{demolition\ rate} * \boldsymbol{construction\ area}\ (\boldsymbol{m^2}) (\text{Verhagen et al.}, 2021)$$

The detailed calculation processes are provided in the **Appendix II - Future urban mining potential and hub capacity** calculation.

2.2.1.2. Step 3: Quantification of the capacity and material efficiency improvement by introducing the Circular Construction Hub in Leiden

In the previous step, the quantity and matching relation between demolition supply and construction demand in the future period are calculated. In this step, the Material Flow Analysis is conducted to help calculate the annual capacity of the circular construction hub.

Firstly, the material flows are analysed under the traditional (the current) construction and demolition waste management system (illustrated in the **Figure 11**). The system builds up a on the yearly basis, including the main processes of construction, demolition, end of life (Eol) material collection, recycling, secondary material production and waste disposal. The model considers the slavery building material (which refers to the total material volume conserved in the demolishing buildings) as 1 of referencing flow, of which, 95% is collected as harvested materials (Schut et al., 2015), and 88% can be recycled (CIRCLE Economy & Metabolic, 2022), 8% can be returned to the value chain as secondary material (CIRCLE Economy & Metabolic, 2022), and 77% of the slavery material are downcycled as backfills (calculated in STAN model).

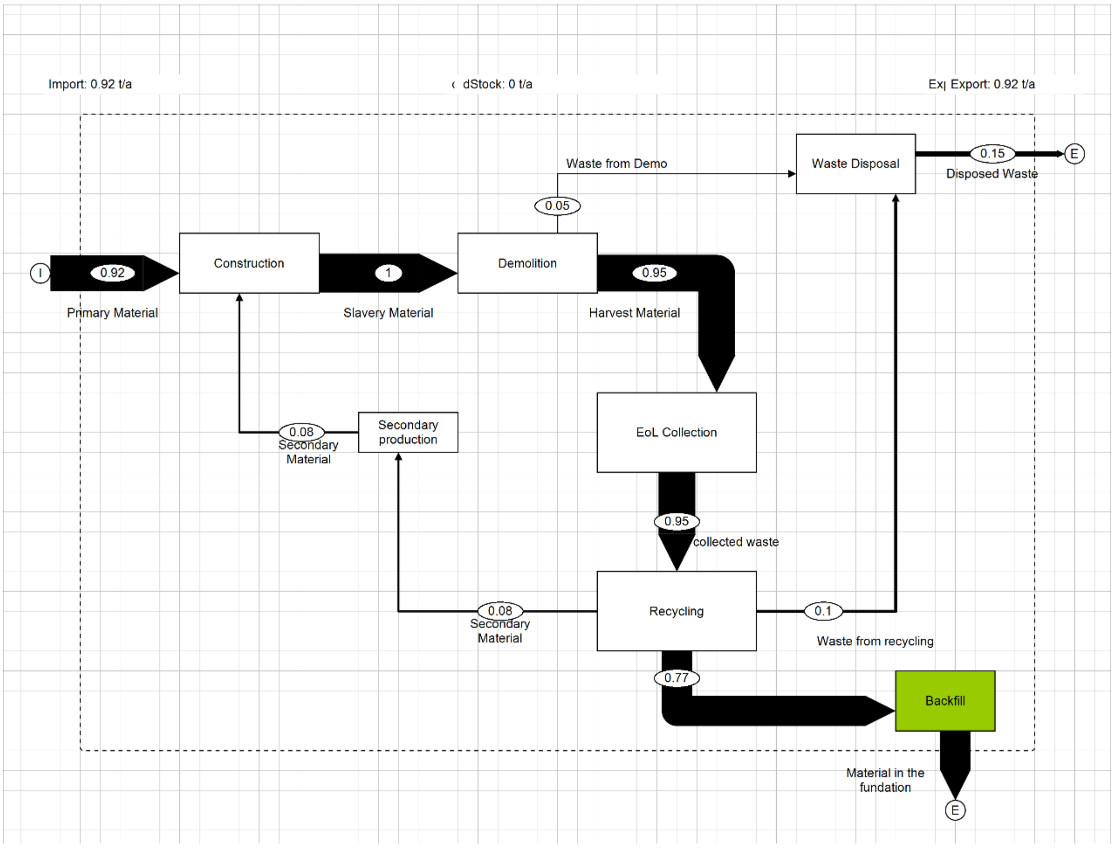

Figure 11 Traditional CDW system demonstration (data integrated from (CIRCLE Economy & Metabolic, 2022))

The **Figure 12** below presents the static model of material flows with the introduction of the circular construction hub in the system on the yearly basis. The system was built upon the concept of the circular construction hub in chapter 3.1, which includes the main processes of construction, demolition, and waste disposal, while the process of end-of-life collection, recycling and backfill are replaced by the circular construction hub process. The model also makes the slavery building material as 1 of referencing flow, and the percentage of harvested material from demolition keeps the same of 95%. From the previous context, 88% of the harvested material can be recycled yet the majority of which are downcycled. With the introduction of the circular construction hub, it is assumed that the 88% of the harvested material can be upcycled for the secondary reuse, therefore, the overall reusing rate becomes 84% (calculated in STAN model), and the demand of the primary material can be reduced to 16% (calculated in STAN model). The calculation of each process follows the mass balance principles.

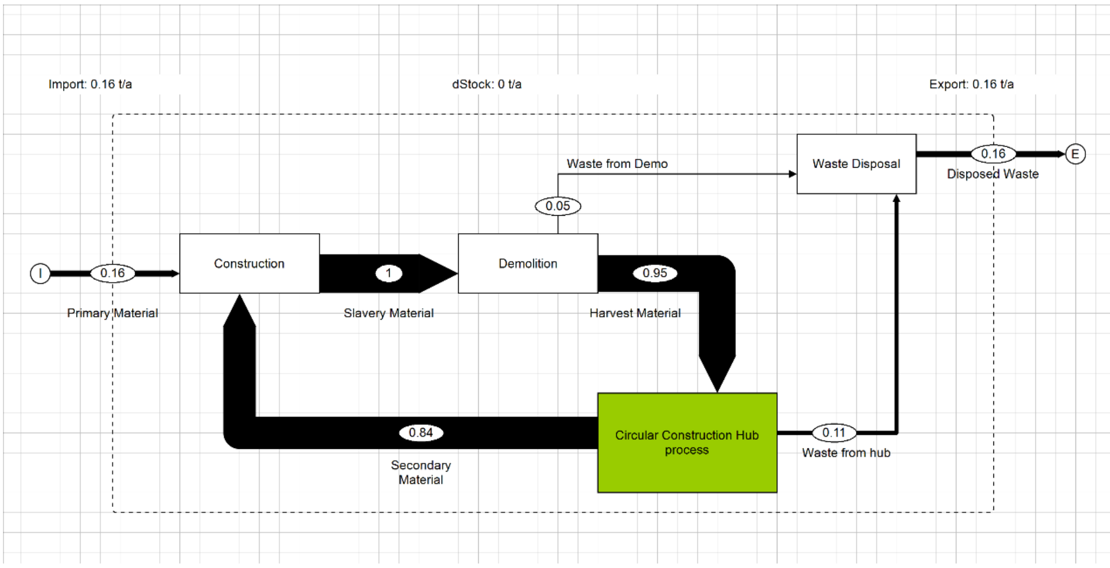

Figure 12 System demonstration with the introduction of the circular construction hub

In this sense, the annual capacity of the circular construction hub equivalents to the corresponding volume of secondary materials that can be saved by the hub each year.

2.2.2. Spatial analysis with Geographical Information System (GIS)

2.2.2.1. Step 4: Suitability analysis of the hub location (based on transportation emission)

The location of the circular construction hub significantly influences the logistical planning. In this section, the spatial analysis based on the transportation emissions is performed to help evaluate the advised location of establishing the hub. Following the previous research by TNO (Anna, 2021), the preferable location of the hub would fulfil the condition of:

easy accessibility for material suppliers, construction and demolition sites, low carbon emission/good environmental performance during transportation, less environmental nuisance such as noises, and stay in distance of residential and ecological areas.

A geographic information system (GIS) is a computer system for capturing, storing, querying, analysing, and displaying geospatial data with location and spatial features, which can be applied for engineering, transport/logistics, management and planning with location intelligence (Chang, 2019). GIS provides information on land use, locations, space capacity, population, etc., which is of great help in formulating circular logistic and supply chain and sustainable urban planning(Andersen, 2007). Hence, GIS provides constructive value for exploring the site location and its transportations.

Firstly, from the previous investigation of the logistics hub in the South-Holland Province (Luik et al., 2021), it suggests that the locations points alongside the national road of N44 and N4 have good transportation accessibility, and have potential to extend the network in the future development. Therefore, the investigation of the location points zooms in to the road of N44 and N4 within the municipality boundary of Leiden. Secondly, to evaluate the GHG emissions caused by the transportation, the transportation load is calculated. The calculation follows the equation below (Yang et al., 2022):

$$\begin{aligned}\boldsymbol{Transportation\ load\ (tons * km)}\\ = \boldsymbol{Material\ quantity\ (tons)\ *\ Transportation\ distance\ (km)}\end{aligned}$$

Of which, the transportation distance between each construction sites and the circular building hub is measured by the straight-line distance of the geometry centre of the construction sites (represents by the polygon in the map, as Figure 10 shows). The material quantity is calculated in step 2 based on the construction plans between 2022-2030.

Therefore, the GHG emission (kg CO2 eq) caused by transportation is calculated by (Yang et al., 2022):

$$\begin{aligned}&\boldsymbol{GHG\ emission\ (kg\ CO_2eq)}\\ &= \boldsymbol{Transportation\ load\ (tons * km)\ *\ 1000}\\ &* \boldsymbol{Carbon\ Emission\ Coefficients\ (kg\ CO_2\ eq/(kg{\cdot}km))}\end{aligned}$$

The carbon emission coefficients (in the Table 2 below) are referenced from (Yang et al., 2022)(Mendoza Beltran et al., 2018); (Steubing & de Koning, 2021) of transportation from ecoinvent 3.6 (kg CO2 eq/(kg·km)) ((Wernet et al., 2016):

Table 2 Carbon Emission coefficients

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034
Truck transportation (SSP2)	transport, freight, lorry 16-32 metric ton, EURO6	transport, freight, lorry 16-32 metric ton, EURO6	RER	0.0002	0.0002	0.0002	0.0002

Based on the calculation results, the site that has the lowest transportation emission is considered as the preferable location of the hub, while the advice of location selection will also consider the practical value such as surface types, environmental nuisance for implementation, detailed discussion is provided in chapter 4.3.

3. Results

In this chapter, the specification of the circular construction hub in the case study of Leiden is provided, the quantification results of building material flows and stocks, urban mining potential, material efficiency improvements and the capacity of the circular construction hub, as well as the site location suggestion of hub are introduced.

3.1. Specification of the Circular Construction Hub

The roles of hubs can be interpreted in various forms with different emphasis of their purposes. Therefore, to fulfil the expectation of municipality of Leiden, and align with the Dutch CE goal, the form and the purposes of the hub are specified to help realize the transition towards the circular construction sector.

Firstly, the hub needs to be defined under the "Circular" context, for which, the outflows from demolition are collected and processed for producing secondary materials, so to help reduce the waste flows, increase the secondary material use and reduce the need for primary materials.

Secondly, it is important to define the objective material type for the hub, so the relevant technology and material flows can be specified. In the research, as the solution to the municipality of Leiden, developing the resource hub (for bulk materials) is less practical, for one thing, the bulk material supplies are nation-wide, some are even global wide, the management of the bulk material flows is beyond the power of the municipality of Leiden. For another, producing secondary bulk materials needs industrial facilities and plants with large scale, as Leiden does not have industry-intensive character, little facilities can support the secondary production for a "Circular hub". More importantly, the layout of the city is already compact, the rich historical and cultural value of the city needs to be preserved, introducing heavy facilities for bulk-material processing and secondary production in the hub would increase the environemtnal nuisance, which is opposite to the expectation. Therefore, for Leiden's solution, the circular construction hub for non-bulk building materials is more applicable.

Accordingly, processing and secondary production of non-bulk building materials require different technologies and facilities. As indicated in the previous paragraph, within the system boundary of municipality of Leiden, heavy industrial facility is not expected as a part of the circular construction hub, therefore, large-scale remanufacturing and recycling in the hub, which may require extra facilities for the secondary production are not the suitable strategies. In this sense, reuse can be a good option to fulfil the "circular" expectation of the non-bulk building materials.

Further, the non-bulk building materials refer to the inert building materials. The metallic non-bulk building materials (such as steel sheets, aluminium sheet etc.,) are not included in the circular construction hub, as the metallic materials themselves are of great market value, the recycling chain of the metallic materials are well-developed, it is unnecessary to improve the recycling rate of metallic materials by the circular construction hub. For inert building materials, concrete, bricks, wood and glass (with the respect of their quantity in the building stock, on average) are the main types of building material in the Dutch building stocks, and consist of the majority of the CDW (Sprecher et al., 2021). However, instead of reusing, the secondary production of concrete is a recycling process, in which, the waste concrete from demolition needs to be crushed into small granulate as secondary raw material, and replace a part of the gravel in the new concrete (van den Berghe & Verhagen, 2021). The full procedure requires large space and heavy equipment (van den Berghe & Verhagen, 2021), which is hard to be realized by the circular construction hub within Leiden. While bricks, wood and glass can be reused or repurposes directly or with simple processing (such as sorting and cleaning), and the reuse and repurpose of bricks, wood and glass are already feasible with technology and market (Schut et al., 2015; Bnext.nl, 2021; New Horizon, 2022). Therefore, bricks, wood and glass can be chosen as the objective material flows for the Leiden's circular construction hub.

Thus, in this research, the circular construction hub considers the bricks, wood and glass as the target material flows, provides the functionality of collecting and separating the construction and demolition waste, processing the collected material into secondary materials for reusing, distributing building materials, storing secondary materials, as well as planning logistics distributions in relation to the construction sites. The concept of the circular construction hub is demonstrated in **Figure 13** below:

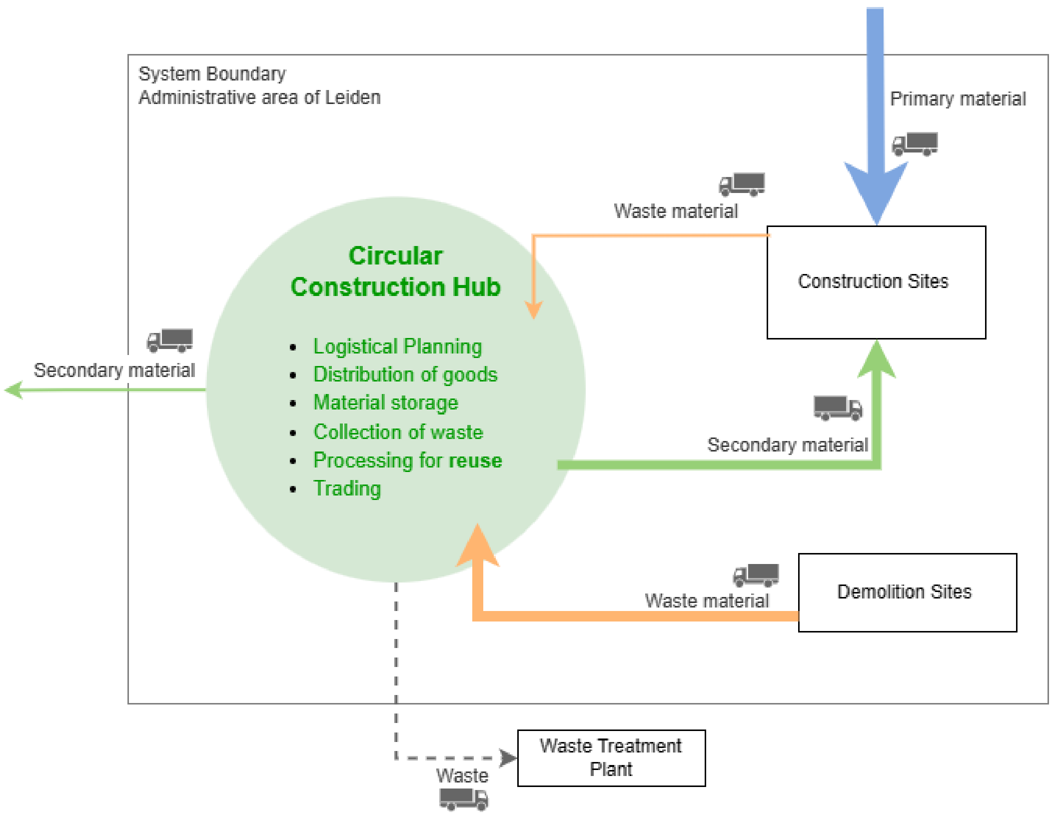

Figure 13 The demonstration of the circular construction hub in research

3.2. Historical and future urban mining potential of the building materials

Following the quantification methods in step 2, (chapter 2.2.1.1), the historical demolition area is calculated as **Table 3** below:

Table 3 The calculation of historical demolition area per building type

year	Total residential area (m2)	Row house (m2)	High rise (m2)	Detached (m2)	Apartment (m2)	Total non-residential area (m2)	Commercial (m2)	Offices (m2)	Others (m2)
2012	44253	12142	19428	572	12112	87765	9074	11627	67064
2013	28791	7899	12640	372	7880	56872	5880	7535	43457
2014	82909	22747	36398	1071	22692	41893	4331	5550	32012
2015	82109	22528	36047	1061	22473	67404	6969	8930	51505
2016	137826	37815	60507	1781	37722	40255	4162	5333	30760
2017	119431	32768	52432	1543	32688	37680	3896	4992	28793
2018	31990	8777	14044	413	8756	50553	5226	6697	38629
2019	45586	12507	20013	589	12477	34170	3533	4527	26110
2020	83175	22820	36515	1075	22765	34638	3581	4589	26468
2021	73311	20114	32185	947	20065	22936	2371	3039	17526

The historical construction area is calculated as **Table 4** below:

Table 4 The calculation of historical construction area per building type

year	Total residential area (m2)	Row house (m2)	High rise (m2)	Detached (m2)	Apartment (m2)	Total non-residential area (m2)	Commercial (m2)	Offices (m2)	Others (m2)
2012	143894	36476	19423	878	87117	533413	18186	66988	448239
2013	137402	34830	18547	839	83186	549456	18733	69003	461720
2014	92262	23388	12454	563	55857	369138	17635	74568	276935
2015	127533	32329	17215	778	77211	241868	4613	40668	196587
2016	205441	52078	27731	1254	124378	326326	6340	73122	246864
2017	177394	44968	23945	1083	107398	307688	10207	50271	247210
2018	147753	37454	19944	902	89453	251190	12133	12999	226058
2019	136674	34646	18448	834	82745	188966	9071	20252	159643
2020	115776	29348	15628	707	70093	206884	7764	8048	191072
2021	198578	50338	26804	1212	120223	353542	10542	30438	312562

The future construction area based on the project planning is calculated as **Table 5** below:

Table 5 The calculation of future construction area

	Project name	Building type	Construction area (m2)	Time start -year	Time end - year
1	Rooseveltstraat 65	office	2004	2021	2022
2	Bachstraat Redevelopment	others	9016	2021	2022
3	Biomistelaan	row house	1626	2021	2024
4	Brahmaslaan 80	single	1172	2021	2021
5	De willem de Zwijgerlaan Oost	row house	96622	2021	2022
6	Groenoord hotels	others	60067	2021	2024
7	Biezpad	apartment	210	2021	2022
8	Lammenschans triangle	apartment	203251	2021	2023
9	LEAD tower	commercial	6774	2022	2023
10	Opaalstraat	apartment	688	2022	2025
11	Ypenburg bend	high rise	6124	2022	2023
12	Lorentzhof hotels	others	8131	2022	2024
13	Rhijnvreugd	others	9789	2022	2023
14	vogelwijk and reaadsherenbuuurt	others	30791	2022	2026
15	Meerburg	commercial	28855	2022	2024
16	Leiden stadhuis	others	3046	2022	2024
17	Sports hall Oppenheimstraat	apartment	25256	2022	2024
18	Vijf Meilaan - De Premier	high rise	1786	2022	2024
19	Westerpoort Hotels	apartment	12506	2022	2024
20	Avenue Plesmanlaan 100	high rise apartment	5835	2022	2024
21	De oude Kooi	row house	14764	2022	2023
22	Telderskade Hotels	others	68083	2022	2024
23	Indoor Sportcentrum	others	5657	2023	2029
24	Turquoise	others	1445	2023	2025
25	Wernink terrain	apartment	77898	2023	2023
26	Roosevelt West	apartment	75161	2023	2025
27	Vondelkwartier	others	61819	2023	2025
28	Watergeuskade	others	13924	2023	2025
29	Professorenwijk-Oost	others	49790	2023	2025
30	Residential units Fruinlaan and Verdamstraat	apartment	2028	2023	2025

31	Parking garage Haarlemmerstraat	apartment	355	2024	2025
32	Hoge Mors	others	76989	2024	2026
33	Humanities Campus	others	10563	2024	2026
34	P.J. Blokhof	apartment	4010	2025	2027
35	Business Park Vliletzone-Midden	others	223897	2026	2028
36	cheese marrket	others	6333	2026	2030
37	Kopermolen	others	10411	2026	2030
38	Corantijnstraat and Paramaribostraaat	apartment	11737	2026	2030
39	Gasthuiswijk and Haagweg zuid	others	175715	2026	2030
40	station area	others	5693	2026	2030

The construction area of each year (differentiated from residential and non-residential buildings) in the future period is listed in **Table 6** below:

Table 6 the calculation of future construction area

year	Total residential area (m2)	Total non- residential area (m2)	Total construction area (m2)
2022	165295	53317	218612
2023	216040	128055	344095
2024	51451	150766	202218
2025	11135	74323	85458
2026	4353	129735	134087
2027	3350	140046	143396
2028	2347	90291	92638
2029	2347	39857	42204
2030	2347	39631	41978

The demolition area of each year (differentiated from residential and non-residential buildings) in the future period is estimated in **Table 7** below:

Table 7 the calculation of future demolition area

year	Total residential area (m2)	Total non- residential area (m2)	Total demolition area (m2)
2022	33801	24020	57821
2023	53202	37808	91010
2024	31266	22219	53485
2025	13213	9390	22603
2026	20732	14733	35465
2027	22171	15756	37927
2028	14323	10179	24502
2029	6525	4637	11163
2030	6490	4612	11103

The **Figure 14** below shows the comparisons between demolition and construction area in the historical year 2012-2021, and the future year 2022-2030. In the year between 2012 until 2021, the construction and demolition activities did not show the evidence of trend with time changing, the amount of the construction and demolition were rather random every year, same as the mismatch between construction and demolition areas. Overall, the construction area was much greater than the demolition area in both historical period and future period, the area of demolition is less than 50% of construction area each year.

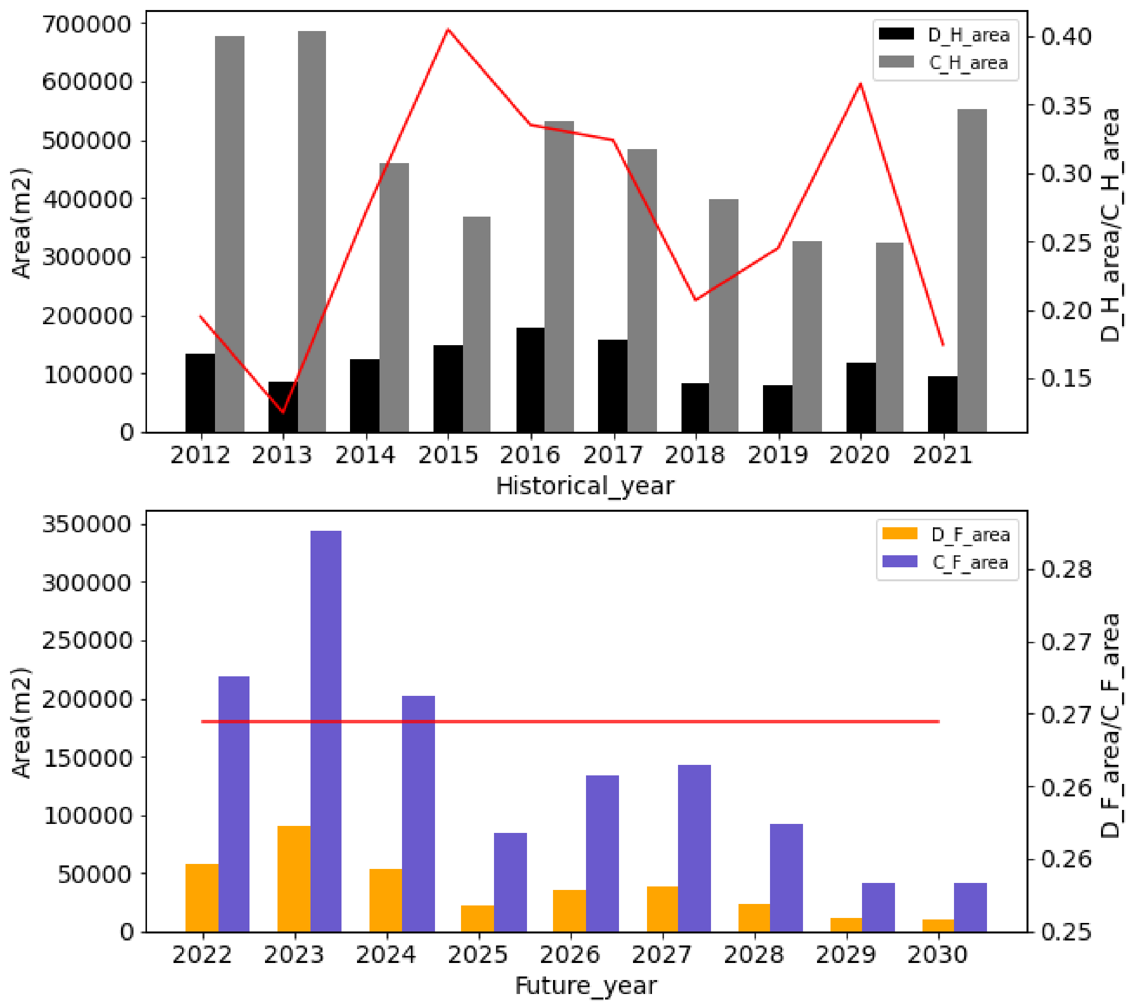

Figure 14 The comparisons between demolition and construction area

Relevantly, shown in the **Figure 15** below, the building material demand by constructions, in terms of bricks, glass and wood, were much greater than the demolition could harvest. In the past 10 years, the theoretically harvested bricks from demolition were only 23% on average of what construction demand per year, respectively, the glass is 15%, and the wood is 32%.

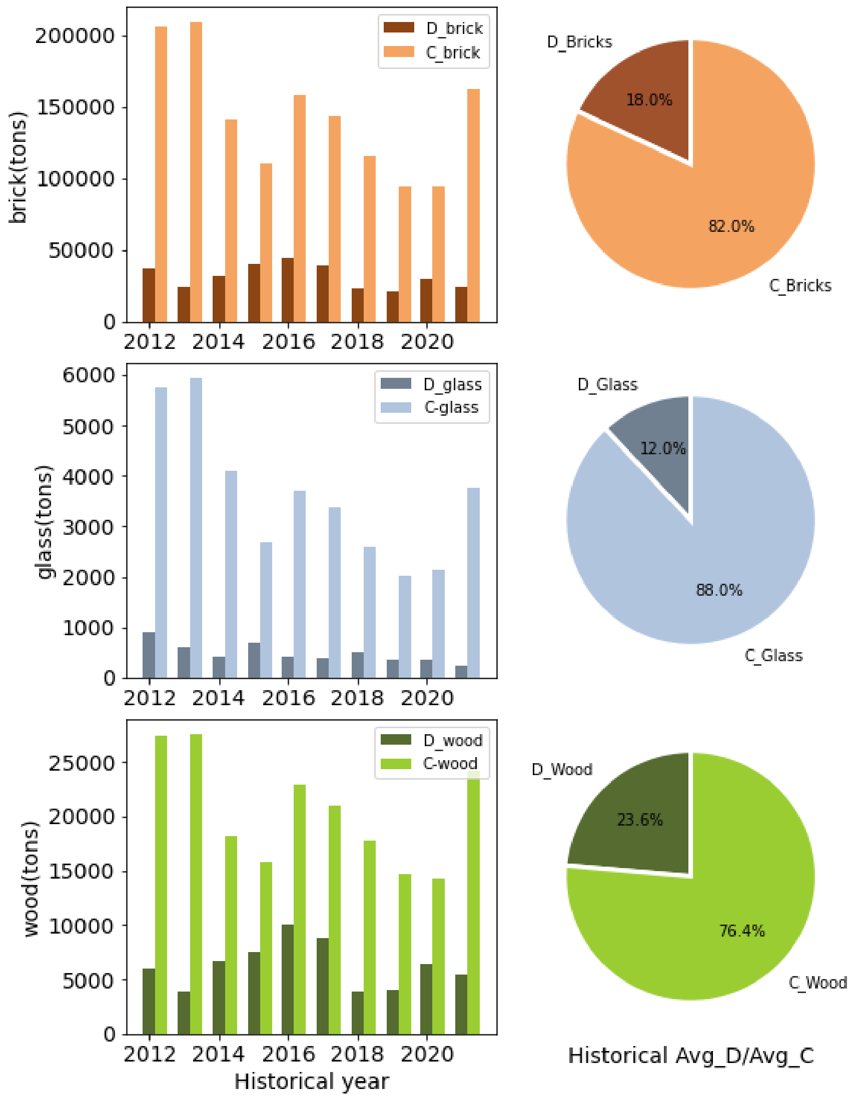

Figure 15 The historical (2012-2021) urban mining potential between demolition waste and construction demand (bricks, glass, wood, respectively)

During 2022-2030, as **Figure 16** shows, the demolition area are much less than the construction area, the predicted material flow of bricks, glass and wood is less than the construction demand, of which, the theoretical amount of demolished bricks flows is 28%, glass is 21%, and wood is 41%, on average per year are much less than the construction area, the predicted material flow of bricks, glass and wood is less than the construction demand, of which, the theoretical amount of demolished bricks flows is 28%, glass is 21%, and wood is 41%, on average per year.

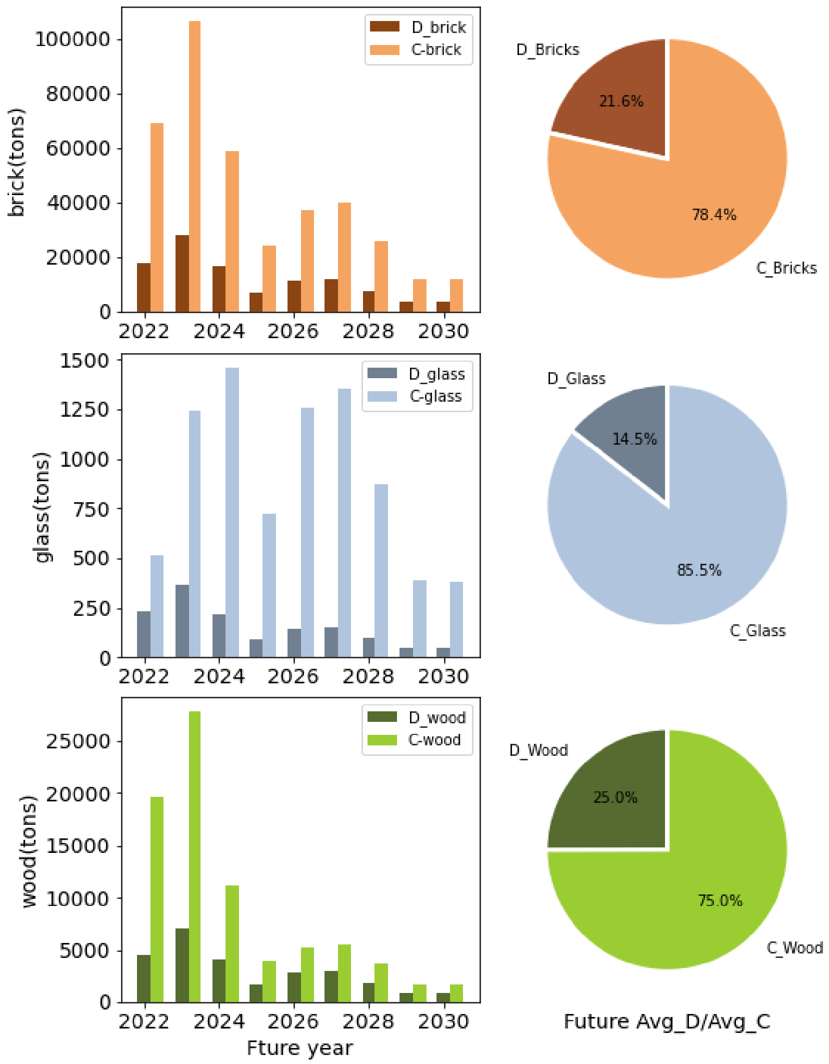

Figure 16 The future (2022-2030) urban mining potential between demolition waste and construction demand (bricks, glass, wood, respectively)

3.3. Material efficiency improvement and the capacity of the circular building hub

Based on the number given in chapter 2.2.1.2, the overall reusing rate becomes 84% (calculated in STAN model), and the demand of the primary material can be reduced to 16% (calculated in STAN model). The **Table 8** in the following shows the quantity of each building material flows that can be collected by the end of life of the building, and can be reused as secondary materials with the help of the circular construction hub.

Table 8 The quantity of materials saved by the circular construction hub

	bricks/tons		glass/tons		wood/tons	
year	EOL	Saved	EOL	Saved	EOL	Saved
2022	16867.5	14337.4	220.9	187.8	4268.7	3628.4
2023	26549.6	22567.1	347.7	295.5	6719.0	5711.1
2024	15602.6	13262.2	204.3	173.7	3948.6	3356.3
2025	6593.7	5604.7	86.3	73.4	1668.7	1418.4
2026	10345.8	8794.0	135.5	115.2	2618.3	2225.5
2027	11064.1	9404.4	144.9	123.2	2800.0	2380.0
2028	7147.7	6075.6	93.6	79.6	1808.9	1537.6
2029	3256.4	2767.9	42.6	36.2	824.1	700.5
2030	3238.9	2753.1	42.4	36.1	819.7	696.7

Correspondingly, the annually average end-of-life collection volume of each building material shows in the **Table 9** below, which refers to the annual capacity of the relevant material in the circular construction hub. According to the material density, of bricks 1709 kg /m^3 (Belén et al., 2018), wood 800 kg /m^3 (Annette Harte, 2009), glass 2500 kg /m^3 (saint Gobain, 2022), the estimated volume of each material in the hub is also demonstrated.

Table 9 The annual capacity of the building materials in the hub

	bricks/tons	glass/tons	wood/tons
The annual capacity (AVG Eol collection, tons)	10877.8	142.4	2752.9
The estimated volume of materials in the hub (m^3)	6365.0	57.0	3441.1

3.4. Suitability analysis of the hub's site selection

The spatial distribution of the construction plan and its material intensity in the future years between 2022-2030 is demonstrated in the **Figure 17** below, the shade of the colour map indicates the material quantity demanded by the relevant construction project. The material intensive projects are largely located on the south area of Leiden.

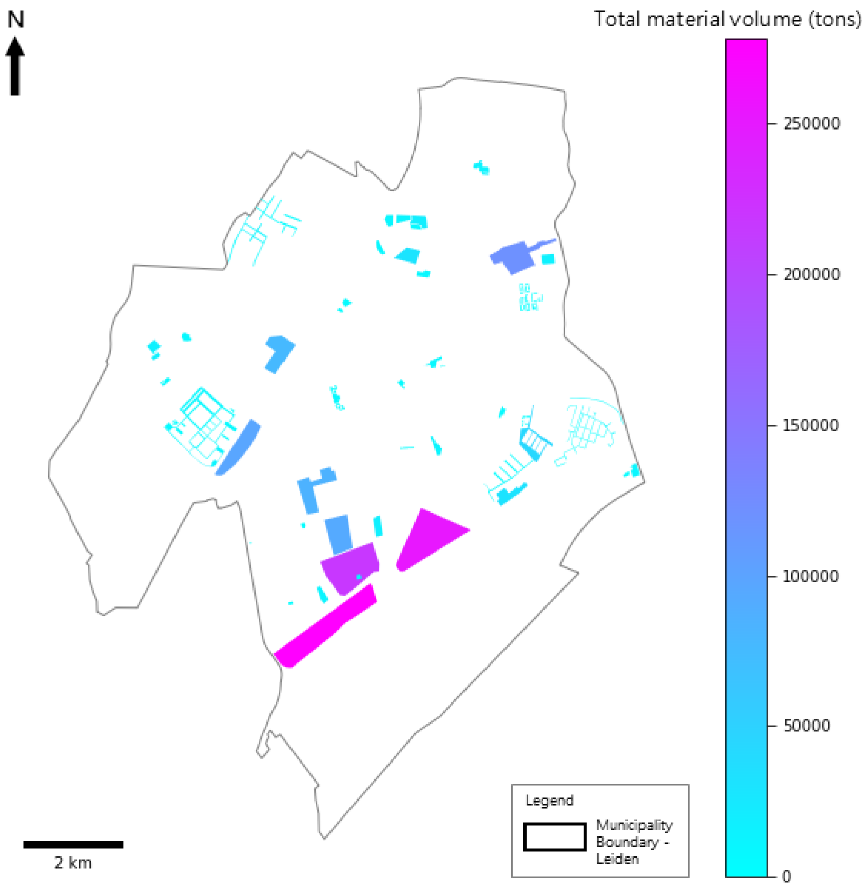

Figure 17 The spatial distribution of the building material intensity in 2022-2030, Leiden

Based on the main national roads of N44 and N4, N44 has length of 2.3 km with the border of Leiden City, N4 is 4.8 km long within the Leiden, shown as **Figure 18**. Hence, N44 was divided into 2 segments with 3 end points, and N44 was divided into 5 segments with 6 end points, to measure the direct distance between the point and the construction location. The results showed, in terms of the transportation load **Figure 19**, the second point, N44-2 has the lowest value on road N44, point N4-4 has the lowest point in road N4, between which, N4-4 is lower than N44-2. Considering the Carbon Emission, the point of N44-2 and N4-4 are predicted to have the lowest emission of its road, N4-4 is 176200 kg eq CO2 less than N44-2, which is Nealy 17% lower.

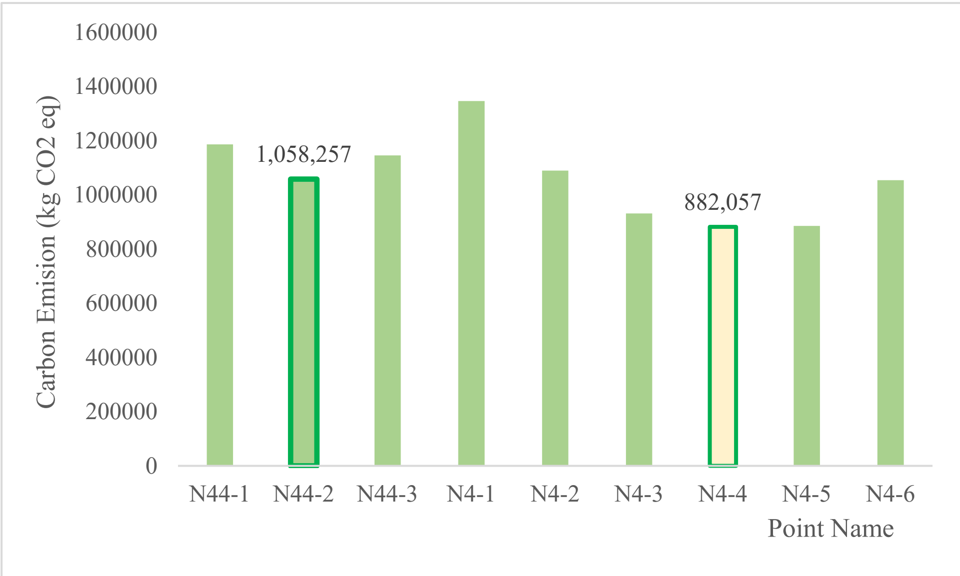

Figure 18 The carbon emission caused by transportations with different selection of the locations

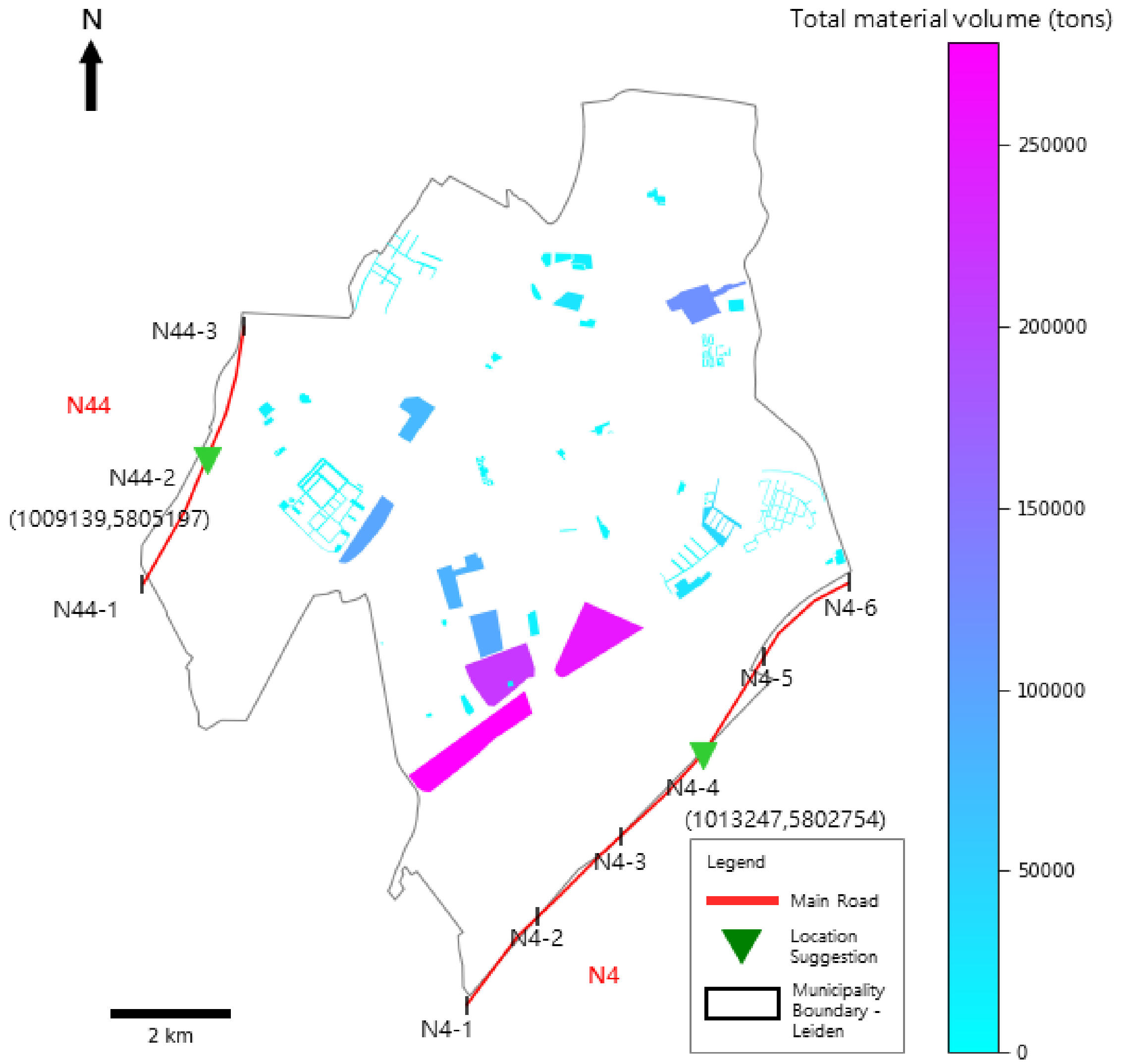

Figure 19 The location suggestions for the circular construction hub based on the results

4. Discussion and interpretation

This chapter analysis and discusses the results from the previous chapter, in order to provide a comprehensive understanding of the solution of the circular construction hub.

4.1. The circular construction hub draws a promising result on accelerating the circular transition in Leiden

The circular construction hub in the research is defined as a comprehensive collective that collects and processes the construction and demolition waste for secondary reusing, distributes building materials, stores secondary materials, and plans the transportation and logistics as well. The conceptual model is an extension of the previous research on the logistics hub(Luik et al., 2021), which not only maintains the traits of low environmental impacts, but promotes the building material reusing as well. The proposed model can be further interpreted with the municipality's planning, in order to help the circular transition of the construction sector in Leiden.

4.2. The urban miming potential of the building stocks cannot fulfil the CE goal under the current CDW management system.

From the results of historical evidence, the construction demand of building material is much greater than what demolition could provide. As figure 13 and 14 showed, each amount of the building material flow from demolition, is less than 50% of the amount demanded by construction, which indicates that, the overall potential of demolition supply cannot fulfil the 50% demand by construction within the construction sector. The evidence was proved again by the calculation of the future possibilities, less than 50% of construction material demand in general can be compensated by the planned demolition supply. Therefore, quantitatively, the Dutch CE goal for 2030, 50% reduction of primary raw material consumption cannot be achieved by "closing the material loop", in other words, supplied by the secondary materials, as the total amount of the construction demand is always much greater than the demolition amount. This finding shows the consistency with the previous study on the urban mining potential in the Netherlands, and the demolition and construction material mismatch in Leiden. Meanwhile, the resource-intensive character will be exiting in the future construction sector.

More importantly, as the building structure and the building material types are changing during the time, for example, more concrete are used in the building structures in the most recent construction projects, while the bricks are phasing out and more applied for aesthetic purposes. Under the current CDW management system and the relation between demolition supply and construction demand, the mismatch of the building material types, and material properties can be predicted to be impeded in the future, the primary material will always be demanded by the construction activities. The arguments find the consistency with the previous study of (Yang et al., 2022)and (Verhagen et al., 2021).

4.3. Secondary building materials can be largely saved with the implementation of the circular construction hub in Leiden

Even though the results from urban mining evaluation confirmed that of the building stock is unable to meet the requirement of the Dutch CE goal by 2030, when comparing with the status quo, the introduction of the circular construction hub still shows the promising performance of the reduction of the demolition waste, the improvement of the material efficiency and the growing share of the secondary material use in the construction activities. The circular construction hub can help to encourage prioritizing the secondary materials use and increasing the awareness of the material circularity to the stakeholders (CIRCLE Economy & Metabolic, 2022; Economy, 2020) . It suggests that the introduction of the circular construction hub shows the effectiveness as the intermediate step on the circular transition. The transition towards circularity is a long-term process, the overall impacts brought by strategies and interventions cannot be determined from single dimension by only matching the demolition waste and construction demands.

4.4. The location of the hub is suggested near road N4

Based on the calculation of transportation load and carbon emission, the point of N44-2 is the option on the road N44 with the lowest transportation load and carbon emission, the point N4-4 is the option on the road N4. In comparison, as the material intensive projects are mainly located near the road N4, the overall transportation carbon emission of the points on road N4 are lower than the points on N44. And point N4-4 has the lowest transportation load and carbon emission. However, the northwest area near N4-4 is the ecological area, park De Bult and the park Polderpark Cronesteyn, where are not the destination of the circular building hub, the final decision of the circular construction hub can be located in the industrial area near N4-5 and N4-6, demonstrated in the Figure 20 below.

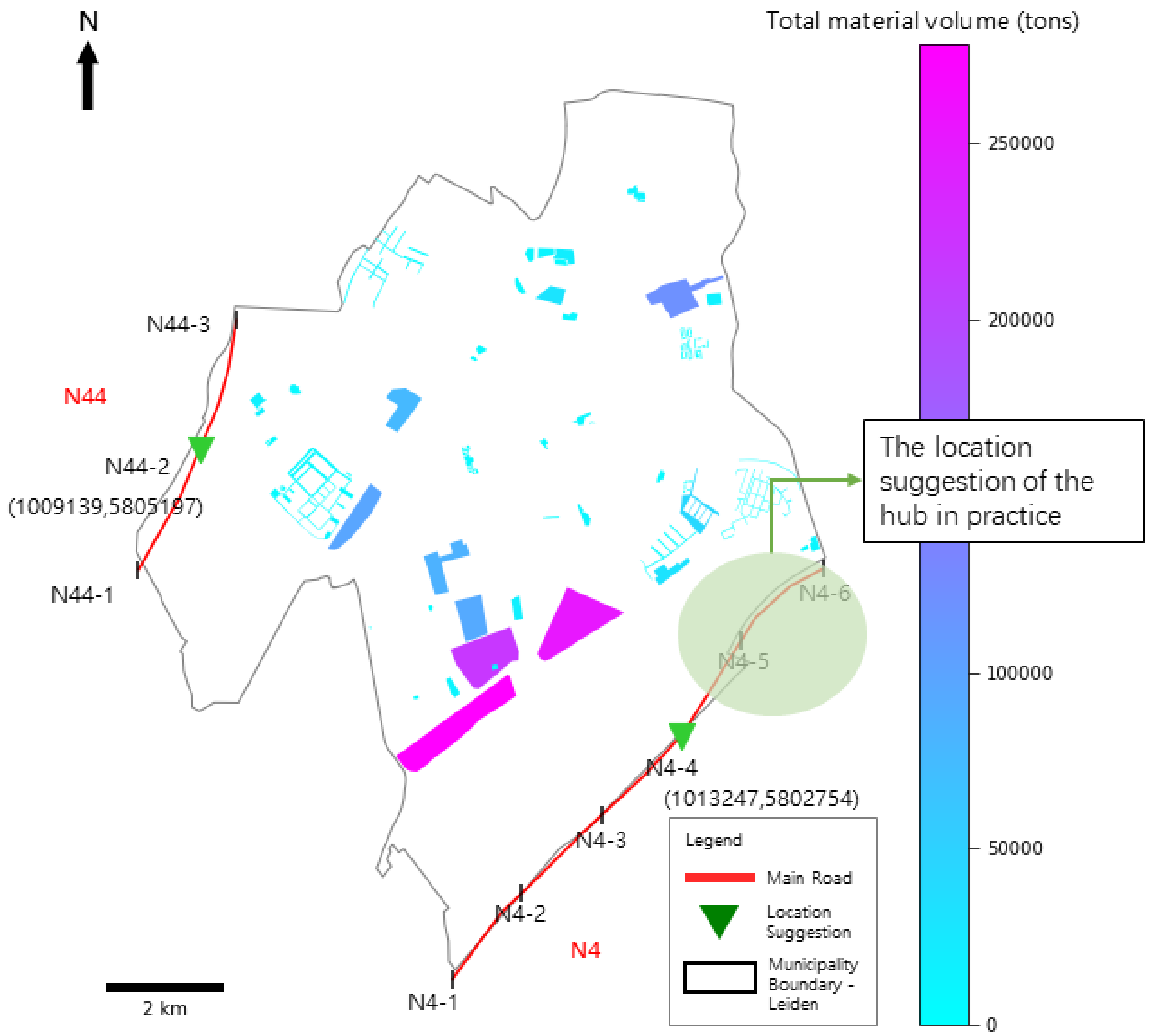

Figure 20 The location suggestion of the circular construction hub in practice

5. Limitations

- **Limited data availability**

Limited data was available to perform quantitative analysis with good data accuracy compared to the actual construction or demolition projects. In the calculation of historical data (2019-2021), the quantity of construction projects and demolition projects are recorded in the different units, and due to the uncertainty of construction planning, the actual construction area and the demolition area can only be determined when the projects are finished. Meanwhile, the amount of material flow and building stocks were calculated based on the Material Intensity in the previous studies, which may not reflect the actual number of the material flows. Additionally, the calculation of the reusing rate and the calculation of the carbon emissions were also calculated based on the data from previous studies due to the lack of data in the real system. However, the full quantitative analysis was performed with logical consistency as described, even though the number may not fit the real data, the scale of the amount is still valid and provides convincing evidence for practical reference. Yet it is highly suggested for the stakeholder to collaborate and build up a uniform data base and information sharing platform, the advanced digital and infrastructure capacity development will largely help to promote the development of the circular logistics (CIRCLE Economy & Metabolic, 2022), which establishes the fundamental support for decision making in practice (Chileshe et al., 2018; Ding et al., 2023; Dixit et al., 2022).

- **Limited dimension on analysing the construction sector circularity**

The research only addressed the quantitative dimension (material flows, logistics flows) on evaluating the impact of the circular construction hub. While the establishment of such collective could bring various positive impacts during circular transition, such as market value, business model development, stakeholder collaborations, urban development etc., which could be evaluated with a better performance on achieving the CE goals. However, due to the lack of information in the current building system, and limited capacity in one research, the comprehensive evaluation of the circular construction from multiple dimensions was excluded, it is suggested to develop the research on impact from different perspectives in the future.

- **Future development**

The circular building hub in the research was a starting point on the transition towards building circularity, few types of building materials, circular strategies were included due to the lack of capacity in the single research. More exploration on the circular strategies, transportation methods, collaborations etc., can be conducted in the future research.

6. Conclusion

From the results and discussion above, it can be concluded that, the introduction of the circular construction hub in city Leiden will have positive impact on the transition towards construction sector circularity.

Firstly, the historical data (2019-2021) and the future construction plans (2022-2030) both showed that the demolition waste from the building stocks cannot fulfil the 50% of the construction demands, which failed the expectation of the Dutch circular economy goals. However, the current waste treatment method, backfill, does not observe the circular strategy, which requires to recover the material value as higher level as possible based on the waste hierarchy. Therefore, it showed the potential of reusing the secondary material from demolition waste, in order to improve the material efficiency. Hence, the introduction of the circular building hub plays the important role in the transition to the building material circularity. By returning the backfill flows to the secondary material market, the circular construction hub can help to reuse and upcycle 84% of slavery building materials from demolition waste to the material value chain, which helps to reduce the demolition waste and increase the secondary material share comparing to the status quo. Relevantly, the demand for the primary material can be reduced from 92% to 16% in the total consumption of the construction materials. As the results of hub's capacity, it is calculated that the material flow exchange of 10877.8 tons of bricks, 142.4 tons of glass, and 2752.9 tons of woods will be expected annually by the circular construction hub.

Meanwhile, the construction sector has strong spatial characterization, which makes the location of the circular construction hub as an important part of the overall solutions. According to the quantification results, the point of N4-4 has the lowest transportation load. Considering the practical manners, the industrial area near points N4-5 and N4-6 can be the selection of the future circular construction hub.

In summary, the current number of the recycling rate is mainly contributed by downcycling, there still a long way to go in the transition towards building material circularity. The circular construction hub can be a good initiative solution to promote the secondary material use in the construction sector, the coordination among stakeholders and the development of the information sharing system are necessary in accelerating the development of the material circularity. Transition is a long process but every effort can make difference, practical solutions should be operated without waiting time, especially for the construction sector.

Acknowledgement

This thesis research is a struggling but meaningful procedure, and draws a good end for my master programme. I would like to say a massive thanks to my supervisor Mingming, and Alexander, they provided me with a lot of insights for my study, and patience and support when I was struggling in developing the research. And I also appreciated a lot for the help from Xining, he offered me lots of practical information on methodology development and research development. I am also thankful to be a member of the interdisciplinary thesis lab of the circular building and infrastructure hub, thank you for the help and support from Saskia and Karel, and the insightful discussion with the fellow colleagues. I not only gained more knowledge on the circular construction sector, but also make a big progress on the self-development.

Sincerely,

Wenhui Shan

List of figures:

List of tables:

Appendix I - Historical urban mining potential calculation

The calculation of the historical urban mining potential is summarized in **Excel file "historical urban mining potential.xlsx".**

Appendix II - Future urban mining potential and hub capacity calculation

The calculation of the future urban mining potential and the capacity of the circular construction hub are summarized in **Excel file "future urban mining potential and hub capacity.xlsx".**

Appendix III - Future construction transportation load calculation, carbon emission

The calculation of the suitability analysis of transportation emissions is summarized in **Excel file "Future construction transportation load calcualtion_carbon emission.xlsx".**

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