Description of material and energy flows of urban building and infrastructure construction

Deliverable D5.1

05/07/2023

WP	5
Dissemination level	Internal
Deliverable lead	AIT Austrian Institute of Technology
Authors	Camille Reynaud (AIT) Daniel Horak (AIT) Ali Hainoun (AIT) Sebastian Stortecky (AIT) Ernst Gebetsroither (AIT)
Abstract	This deliverable provides an overview on material and energy flows of urban building stock and infrastructure. It elaborates on building stock inventory, modelling, and evaluation tools of CE for application on building stock and infrastructure
Keywords	Building stock and flow, Secondary materials, Life-Cycle Assessment (LCA), Circular economy

Revision History			
Version	Date	Modified by	Comments
V0.1	08/06/2022	Daniel Horak & Ali Hainoun (AIT)	First draft
V0.2	15/11/2022	Camille Reynaud (AIT)	Structure adaptation, literature review findings.
V0.3	13/02/2023	Camille Reynaud (AIT) and Daniel Horak (AIT)	Literature review findings. Description of the stocks and flows models at city level in the case study cities: Rennes, Gothenburg, Njimegen and Vienna.
V0.5	27/02/2023	Ali Hainoun (AIT)	Review
V0.6	13/03/2023	Camille Reynaud (AIT)	Template adaptation and content review.
V0.65	26/03/2023	Ali Hainoun (AIT)	Complete Review and adaptation
V0.7	04/04/2023	Camille Reynaud (AIT)	Integration of comments and corrections from partners: Vincent Augiseau (CiteSource) Maud Lanau (Chalmers University) Angeline Chartier (Wageningen University)

V0.8	24/04/2023	Leonardo Rosado (Chalmers)	Complete review and comments.
V0.9	05/05/2023	Camille Reynaud (AIT) and Daniel Horak (AIT)	Integration of comments and adaptation.
V0.95	29/06/2023	Leonardo Rosado (Chalmers)	Final review and final comments
V1	05/07/2023	Daniel Horak (AIT) and Camille Reynaud (AIT)	Integration of comments, review of English and fine tuning of the layout.

Approval			
Version	Date	Validated and approved by	Comments
V1	02/10/2023	Leonardo Rosado (Chalmers)	

TABLE OF CONTENT

List of Figures

List of Tables

LIST OF ACRONYMS AND GLOSSARY

CE	Circular economy
C&DWs	Construction and demolition wastes
CREATE	**Embedding advanced urban material stock methods within governance processes to enable circular economy and cities resilience**
GHG	Greenhouse gas
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
ULLs	Urban Living labs
MFA	Material Flow Analysis
SM	Secondary Materials (any construction material that have been recycled or reuse after the end of their useful life)

EXECUTIVE SUMMARY

The CREATE project aims at supporting the urban transformation towards sustainable, resource efficient and low-carbon economy with focus on assessing the role of circular economy for the urban infrastructures and communal assets covering buildings, municipal roads, water, and wastewater pipes. It works on establishing an inventory of the existing material stocks within urban construction, developing reliable scenarios for future expected material flows, and providing governance arrangements and capacity building on how to approach the circular economy transition. In its overreaching goal the project will contribute to decarbonizing building and construction sector and help cities to achieve their climate neutrality goals. The project applies a co-creation process with key stakeholders of the Urban Living Labs (ULLs) to demonstrate the application of CE for material stocks and flows and evaluating the resulting impacts in terms of resource and embodied energy saving and CO2-emission reduction. Results achieved and lessons-learned out of the ULLs will provide tailored governance arrangements and build the basis for further upscaling and replication on urban CE.

Within this context, this document provides the first deliverable (D5.1) of WP5 “Impact assessment and evaluation of circular economy” dealing with the application of the concept of circular economy in the Built Environment and **evaluating the associated environmental impacts**[1]. For this purpose, WP5 will be using existing modelling tools and databases for LCA and applying a scenario-based modelling approach combined with a participatory process involving relevant stakeholders.

Deliverable D5.1 makes an inventory of existing modelling approaches for LCA in circular economy for urban construction by listing and discussing available data sources, modelling tools, and challenges around the reuse of secondary building materials. It concludes with an overview and comparison of modelling tools and databases that provides the basis for the selection of the modelling approach to be used in the assessment of the implementation of circular economy

[1] Subject to data availability, simplified evaluations of economic impacts will be provided

principles in Gothenburg, Nijmegen, Rennes, and Vienna based on material stock and flow analysis.

The current state of knowledge related to mapping and analysis of stocks and flows of urban construction materials has been reviewed and evaluated with focus on the objectives of the CREATE project. An analysis about the role of the Built Environment in circular economy strategies is provided alongside elaborations on the differences between information on the material and component level. The review indicates clear benefits in considering stocks from the Built Environment and urban construction flows on the component level due to higher relevance in the waste hierarchy and in construction markets. Component level considerations are, however, related to increased efforts in data procurement, and currently applied modelling approaches do not always match the status of data availability in cities. The review covers commonly applied methodologies in the fields of material flow analysis (MFA), Economy-Wide Material Flow Analysis (EW-MFA), energy flow analysis, and material stock analysis. The mapping of materials and component stocks receives special attention as it is crucial for the formulation of circular economy strategies and play a key role in the scope of this research project. It was found that a thorough characterization of material and component stocks is vital, as their location and technical reuse/recycling potentials highly influence the environmental and economic implications of their use in new constructions and refurbishments Ultimately, the review of methods deals with the integration of stock and flow analyses in LCA models to provide a reliable estimation of the environmental (and economic) impact of circular economy strategies that focus on recycling and reuse. Life-cycle stages of buildings and urban infrastructure are discussed in relation to the applicability of secondary material recycling and components reuse. This topic is essential for the quantitative assessment of CE role in driving urban transformation and will be addressed in the forthcoming deliverable (D5.2) which will build upon D5.1 and provide more detailed elaborations on the life-cycle inventory (LCI) of the selected case studies, as it will establish the techno-economic models for the material supply chains in the ULLs.

Modelling of CE using LCA approach relies on the availability of consistent data of the considered ULLs. Hence, the deliverable reports on the currently available material stock and flow data in the pilot cities and the selected living labs following a general outline on modelling construction material stock and flows. For this purpose, the available studies for Gothenburg, Nijmegen, Rennes, and Vienna are compiled and discussed upon the applied methodologies and prevailing material use. It reveals that all cities provide assessments on the material level where the most used and recycled material across the pilot cities is concrete. Following characteristics have been identified by the ULLs cities and pilot city Vienna:

- Gothenburg integrates components to the highest level of detail within the sample. Buildings are modelled by construction elements, *e.g.*, walls, slabs and construction elements are further differentiated by construction materials and build periods
- Rennes stands out as notable example, as the existing analyses provided by CitéSource include building material stocks and flows, and cover recycling facilities and their locations. This will facilitate the development of LCA models that are tailored to the region-specific context [1].
- In Nijmegen, data availability seems to be comparably limited. The consultancy Metabolic, being responsible for the latest study about construction and demolition waste in Nijmegen indicated that an updated and more extensive study could be provided with reasonable effort [2].
- Vienna has been the subject of many research activities regarding construction material stocks and flows. The studies provide insights into the spatial and temporal development of material stocks in buildings and infrastructure [3,4]. The review underlines the importance of concrete and brickwork in the material stocks and flows. Furthermore, recycling scenarios for the most important material flows are derived from literature.

The critical evaluation of existing LCA tools regarding their applicability within the CREATE project to serve the defined use cases reveals that the open-source modelling tool “OpenLCA” and the commercial database “Ecoinvent” provide the best choice and thus has been selected to develop the assigned project use cases in the pilot cities.

The review and assessment conducted in this report provide insights into the concepts, tools and data needed to conduct construction materials flows and stocks and LCA analyses to evaluate the environmental impact of recycling and reuse in the built environment.

1 INTRODUCTION

Construction materials - such as cement, sand and gravel, crushed stone, asphalt, and other aggregates - comprise the largest material stock accumulated in modern society. During the last century, the amount of material stocks increased 23-fold worldwide [5]. The unprecedented growth of stock is directly linked to high resource consumption, increased waste discharges, and increased embodied energy and associated GHG-emissions. A large share of material stock accumulates in the urban built environment calling for the need for urban circular economy [6]. By recovering material stocks that become available at the end of use, *i.e.*, feeding material outflows back into the construction system, the accumulated material stock can be accessed to positively influence the material flow balance, while supporting a certain degree of construction activities, potentially leading to reduced primary material consumption and CO2 emission. However, as shown by the example of Vienna, the desired reduction of primary raw material consumption requires more than the implementation recycling and reuse measures [7]. Enhanced knowledge on material stocks and flows in urban construction is therefore required to implement effective strategies for the implementation of a circular economy. CREATE aspires to contribute to this needed knowledge gain by mapping urban construction material stocks and flows, providing impact assessments for the implementation of circular economy principles, and facilitating the implementation of new policies towards circular economy. The establishment of material stock and flow models in the participating living-lab cities is an integral part of WP 2 and serves as input for the subsequent LCA assessment in WP 5. As deliverable D5.1 aims to outline the current situation in living labs related to construction material stocks and flows, an analysis of available data and prevailing practices in the field of urban construction material stock and flow analyses and modelling is required.

The circular economy (CE) approach offers a response to the sustainable development goals regarding a sustainable, efficient, and low-carbon economy. It contributes to tackling the challenges and negative impacts of the current economic model. Its promise is to help achieving a gradual decoupling of economic growth from the consumption of finite resources. Applying this principal at urban scales is encouraged by the various synergies embedded within the cities with their high density of consumption and inefficient resource use. CREATE will make use of CE to support circularity for efficient use of resources and to enable the recycling and reuse of built materials. The **overarching goals** of the project are to:

- develop and visualize an overview of material stocks and flows that are part of the built environment
- provide tailored software solutions to cities that support a circular built environment

- co-create governance arrangements that enable a broader participation of stakeholders, experimentation with decision-support information, and the upscaling of best practices

This deliverable report is part of WP 5, which deals with the impact assessment and evaluation of circular economy for urban construction in the living labs (ULLs) Gothenburg, Nijmegen, Rennes, and Vienna. As part of the impact assessment and evaluation of circular economy strategies, deliverable 5.1 reports on currently available studies and data on material and component stocks and flows in the Built Environment in the ULLs. Combined with the collected stakeholder needs from WP 2, this review serves as basis to assess the possibilities to apply LCA approaches in each ULL to evaluate circular economy strategies in the respective urban construction sector. The report consists of three chapters. Chapter 2 starts with an elaboration on the current state of knowledge in material stock and flow modelling for urban construction and its relation to circular economy. Chapter 3 provides an overview of the best practices from the urban decision support schemes, governance arrangements, and initiatives on circular economy in the EU and at national level of project countries. Chapter 4 elaborate on the stock and flow data in the ULL cities where existing data is gathered, discussed, and compared.

2 STATE OF KNOWLEDGE

The following chapter introduces the state-of-the-art practices to assess urban construction material stocks and flows, their environmental impact through LCA, and the specificities to consider in circular economy strategies for the built environment.

2.1 Urban construction material stocks and flows: scope of analysis

Urban construction material stocks are not only large, but also diverse. Before detailing in currently applied modelling approaches, the following lines give an overview on the circular economy strategies and modelling scopes that can be applied in urban construction.

2.1.1 Existing circular economy strategy for construction materials and components

Circular economy practices in the built environment can be based on several strategies, while there is no commonly accepted definition of circular economy in the building sector and uniformization of the existing circular economy strategies used in buildings and infrastructures.

The existing literature proposes different ways to categorize the existing circular economy strategies in buildings. For example, Lei et al. [8] elaborate on three categories of circular economy strategies based on three principles: closing loop (open-loop recycling and closed-loop recycling), slowing loop (design for disassembly and refurbishment) and narrowing loop (reduce the amount of material used).

An alternative to this categorization is to sort the CE strategies per building life-cycle stages. Ruiz et al. [9] developed a theoretical model approach for CE implementation to reduce waste in the construction sector based on 14 CE strategies that cover the five life-cycle stages of buildings: (i) preconstruction, (ii) construction and renovation, (iii) collection and distribution, (iv) end-of-life and (v) material recovery and production. Akhimien et al. [10] apply a similar methodology in a review on the application of CE in buildings. The review results in the identification of seven main CE strategies, divided as follows within the 4 different life-cycle stages: (1) Product manufacture (design for disassembly, design for recycling, building materiality), (2) Construction: circular building construction methods (3) Operation: building operation in line with CE principles, optimization of building parts for durability and longevity (4) EOL: end-of-life program and loop systems to restore, reuse or recycle components. Another example can be found in the latest flagship report developed by the UK Green Building Council on "how circular economy principles can impact carbon and value" [11]. It proposes 13 CE strategies, divided into five principles of CE in construction: maximize reuse, design for optimization, use standardization, product as a service and minimize impact and waste.

This diversity has resulted in several attempts to consolidate circular economy strategies for buildings. Among them, Ebernhart et al. [12] developed a taxonomy of CE strategies in buildings based on the relation to general CE strategies (reduce, reuse, repair, refurbish, remanufacture, recycle and recover), the project stage, the level of application (building, component, material), and the level of readiness of the technology. Seven CE strategies are particularly relevant at the material level: material selection and substitution, use of secondary material, durability, material optimization, shape optimization, material storage, and symbiosis/sharing of material. At the component level, consolidated, *i.e.,* with a high level of readiness, circular economy strategies include easily assembled/disassembled components, modular components, prefabrication, standardization, reuse of existing components, optimized shapes and accessibility (also known as open design).

2.1.2 Construction materials

Buildings consist of several elements that ensure its primary and secondary functions, *e.g.*, transfer of weight loads, thermal insulation, transmission of light, and these elements are comprised of different components and sub-components, *e.g.*, frame and glass of a window. While some stock and flow analysis examine these components directly [13], most stock and flow models for urban construction focus on construction materials like concrete, metals, glass etc. [14]. This subchapter deals with construction materials and their role in stock and flow modelling and circular economy strategies.

The construction materials found in urban buildings and infrastructure comprise concrete, brickwork, steel, glass, plastics, asphalt and other road aggregates, and copper, as exemplified by the material stock analyses that have previously been carried out in the living lab cities [1,4,15,16] (detailed presentation to be found in chapter 4). Following this focus, many strategies on primary material consumption reduction and practices related to the reuse of these materials involve recycling of demolition wastes [7]. While this focus stands in contrast to the order of priority found in waste reduction principles [17], it is the subject of many assessments of circularity in urban construction.

In contrast to construction components, construction materials often require significant treatment to be reused or recycled in a new construction project. The material sheets reuse toolkit, developed in the Opalis project, provides a comprehensive overview on the reusability and required treatment processes for construction materials and components [18]. In France, this inventory of secondary components and materials is supported by new regulations, as since 2020, the "diagnostic Produits-Equipements-Matériaux-Déchets (PEMD)" is mandatory for each construction site with a GFA > 1000m2 and requires to conduct an inventory of the reusable resources (materials or components) [19]. End-of-life concrete is a common example for the recycling of construction and demolition waste in material form. The recycling process involves the selective crushing of building structures that contain concrete, followed by several separation procedures that decontaminate the recycling aggregate and sort the different size fractions [20]. The obtained aggregates can then be reused in the replacement of natural aggregate in concrete production, potentially reducing greenhouse gas emissions related to concrete production by 65 % [21].

While the recovery of construction components and construction and demolition waste (C&DW) in the form of construction materials often requires recycling [13], recycling is considered inferior to reuse in the waste management hierarchy [22] as shown in Figure 1 . Furthermore, efforts for material recovery of concrete and metals can undermine efforts in the reuse of components [13].

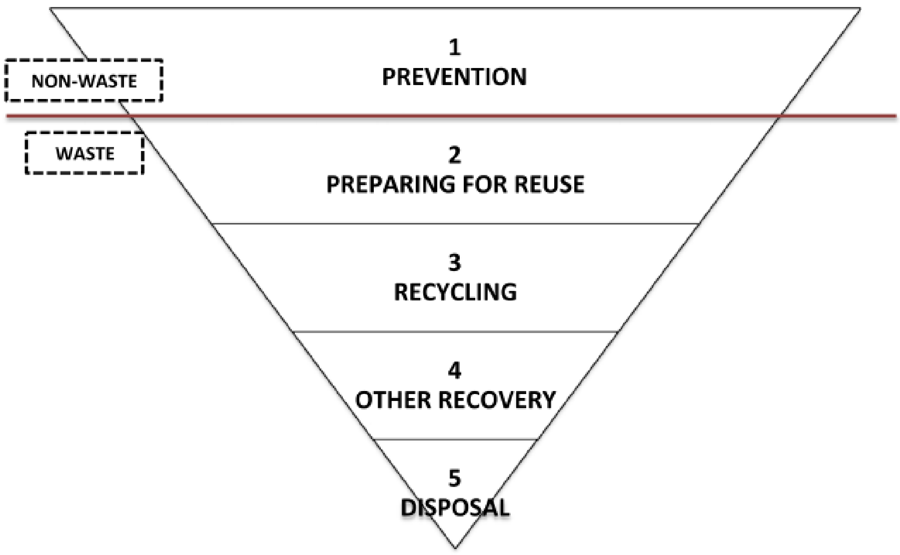

Figure 1 Waste hierarchy according to WFD2008, image from [22]

In summary, it can be noted that urban stock and flow analysis mostly focus on the material level, as data is more attainable than on the component level, and currently applied circular economy strategies in urban construction often relate to recycling.

2.1.3 Construction components

Urban material stock and flow analyses often solely consider material stocks in the form of construction materials like concrete, wood, glass, plastics etc., even though these materials are integrated into buildings in the form of complex assembled construction components [14]. Unlike construction materials, which in many cases need to be treated in some way to be reused in a new construction project, construction components like doors, windows pipes etc. require considerably less treatment, and in some cases no further treatment to be reused. Hence, they could be suitable for direct reuse instead of recycling, which has been demonstrated to be environmentally superior to recycling approaches and ranks higher in the waste hierarchy [22]. Their reclamation, however, requires careful dismantlement procedures to ensure their reusability [23,24]. This process of reclaiming components from unused or to be demolished buildings is sometimes referred to as **'urban mining'**. Arora et al. offer a practical study on the efforts related to manual building component reclamation prior demolition [13]. Their results indicate the practicality of urban mining in the context of the chosen case study and demonstrate related dismantling times and efforts for over 30 types of construction components. Figure 2 illustrates the manual work related construction component reclamation, investigated in [13]. However, the viability of reclaiming components must also be put in perspective of market acceptance of secondary, used components. The Opalis project compiled a comprehensive overview of construction components and their reusability [18]. Furthermore, construction component standardization is seen as an important means to achieve building design for disassembly, which facilitates the reuse of construction components. Current research investigates the prevalent advance in building component standardization and the uptake of standards in industry [25]. It is concluded that the ISO 20887 standard introduces the concept of design for disassembly and the reuse of building components, however, without underlying standards that define these standardized building components. Problem areas that obstruct the uptake of standardized building components were identified in the protectionism of contractors, the protectionism of manufacturers, and a lack of awareness for circular economy among designers [25].

Figure 2 Building component dismantling process [13]

Compared to stock and flow assessments on the material level, consideration of building components requires more knowledge and more granular information about the given urban context [14]. This increased effort in stock and flow modelling is incentivized by increased reusability of construction components over materials, which is regarded superior to material recycling [22]. Additionally, information on the component level brings circular economy concepts closer to market applicability [14]. Therefore, strategic information on urban construction components and their properties can be crucial in the development of circular economy strategies. Current practices for urban stock and flow analyses should be extended by introducing the construction component level to their considerations [14]. This would allow a further development of circular construction strategies as more granular information is required to assess the potential for construction component reuse. Beside Arora et al. [14], recent material stock and flow analyses already start considering the component level of buildings and also differentiate across built years and construction qualities [26].

2.2 Modelling approaches for urban stocks and flows

The implementation of circular economy strategies in urban areas can greatly benefit from the characterization of resource use and waste generation obtained with material and energy flow accounting methods. This section provides a comprehensive review of these methods, specifically in their application at the urban level and within European case studies. These modelling methods offer a structured approach to monitoring the inflow and outflow of materials and energy within the built environment, and their effect on resource depletion. The applicability of these methodologies is dependent on the availability and reliability of data on material and energy flows; thus, this section also details crucial data sources and types needed for their application. Finally, a focus is put on the modelling of secondary materials flows.

2.2.1 Existing urban stocks and flows modelling methodologies

The implementation of circular economy strategies for construction material require to know where, how, and when the secondary materials are available. Indeed, the temporal availability, the type of materials available, and the quality of secondary materials depends highly on the local and regional contexts [27]. Especially, the spatial distribution and temporal availability of material stocks influence the potential for circularity [28]. The quantification of inputs, outputs, and changes in stocks of energy and materials in the urban context can be referred to as urban metabolism [29]. As shown with the extensive review of stocks and flows studies of the built environment, the number of studies to characterize and quantify construction materials and energy flows at urban level have been rising during the past decades [30,31].

The following section introduces currently applied methods and ongoing research efforts with regards to the identification of urban material stock and flows with focus on the construction sector, as well as their limitations.

As a result from the H2020 project “CityLoops”, Hoekmann and Bellstedt provide a comprehensive review of 29 modelling methods for the accounting of urban material stocks and flows [32]. Following the scheme of [33], they differentiate several flow analysis methodologies including material and energy flow analysis, energy assessment, Input/Output, footprint, life-cycle assessment, and integrated methods. Almost half of the 194 case studies included in the review are based on flow analysis methodologies. Three methods are particularly interesting to account for the stocks and flows necessary within CREATE.

Material Flow Analysis (MFA): One of the most widely applied material accounting methods is the Material Flow Analysis (MFA). The main strengths of this methodology, highlighted by Hoekmann and Bellstedt [32], are the possibility to be adapted to specific needs, the number of existing case studies, and its simplicity, which facilitates the communication of the results to a wide audience. However, there is a lack of a single methodological framework that leads to discrepancies between the different studies conducted. MFA provides useful information regarding resources use, production steps, material losses and waste generation. Therefore, it can also be used to collect the necessary data for the LCA inventory phase.

In the context of circular economy, MFA can be used to analyse the quantity of resource import and export flows and to calculate the material consumption. Eberhardt et al. developed a decision-making methodology for CE strategies based on the combination of life-cycle assessment and MFA [34]. In this model, the material flow analysis considers virgin, non-virgin, renewable, and non-renewable material flows as material import. Reuse, remanufacturing, recycling, biodegradation, incineration for energy recovery, and discarded flows are considered as export. Therefore, the total material consumption is calculated by subtracting reused, remanufactured, and recycled flows from the total import.

In a review on circularity metrics Corona et. al [35] mentioned MFA as a circularity assessment tool and distinguish two types of MFA: i) the MFA accounting that analyses all the materials entering and leaving the systems to enable comparison between the systems and ii) the MFA modelling that aims for a better understanding of the dynamics of a given system and can help forecasting. In both cases, the need for further environmental indicators to assess the system's impact is highlighted [36].

Economy-Wide Material Flow Analysis (EW-MFA): The Economy-Wide Material Flows Analysis methodology was developed by Eurostat (also known as the Eurostat method). The methodology is based on measuring the flows entering and leaving the economic system. The inflows are referred to as domestic extraction and include the materials extracted or moved for human processes. The outflows are materials released in the natural environment as residual material, called domestic processed output [37]. The major advantage of this methodology is the good documentation, as it has been used since 2008 by Eurostat [32]. However, it requires a large amount of data. Within the project CityLoop detailed in 3.2.1, three main issues for using the methodology at the city level were identified [38]. Firstly, there is no distinction between flows from city resources and flows transiting through the city: this leads to a risk of overestimating resource consumption. Secondly, the geographical scope of the methodology does not enable accounting for the recycling plants or refurbishment factories located outside of the city boundaries, which can lead to a wrong estimation of waste flows.

Further research has been conducted to overcome those issues. The UMAn (Urban metabolism analyst) model developed by Rosado et al. [39] helps overcoming the main gaps of the EW-MFA model at city level. It provides a decoupling of cross flows from imports and exports to better understand their origin, destination, and magnitude. This is achieved by characterizing the supply chain by combining products and material compositions trough their 5 life-cycle phases (livestock, raw materials, intermediate products, final goods, and waste) to better identify the economic activities involved within the metropolitan area and distinguish import and export flows. Further developments also enable to account for circular economy strategies, especially recycling within the system, as presented in Figure 3 **Error! Reference source not found.** [40].

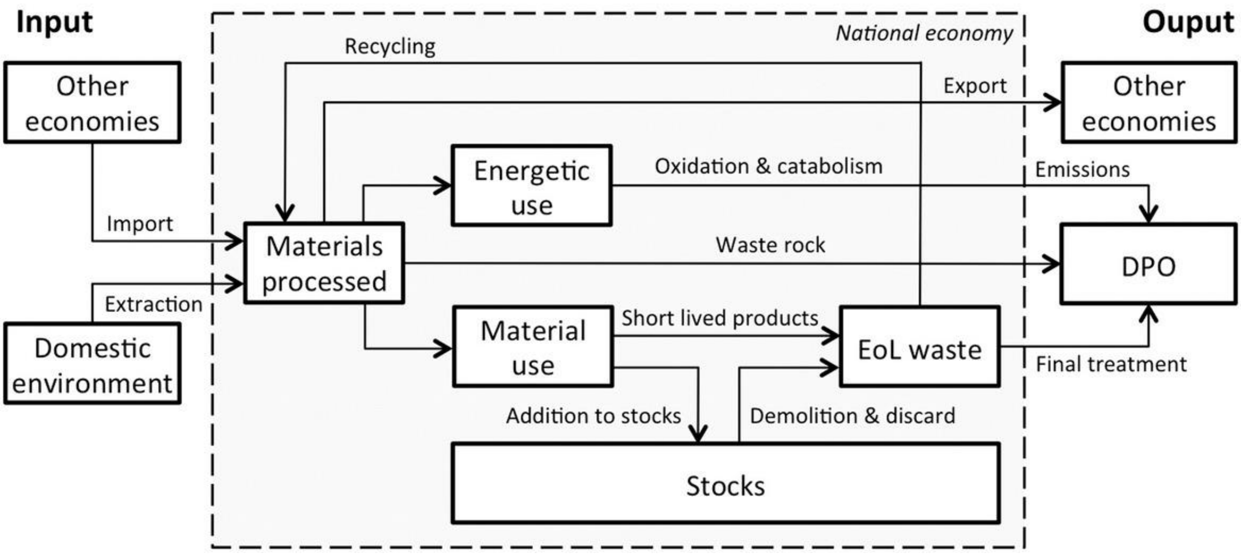

Figure 3: Adapted EW-MFA to account for CE strategies as proposed by Nußholz et al. [41]

Mayer et al. built on this CE assessment and expanded it to other CE strategies, such as reuse, remanufacture, and downcycling, as presented in [42]. This adapted methodology calculates the recycling and recovery material flows directly from the waste statistics. The direct calculation of the flows is impossible for CE strategies that target product life extension such as reuse or remanufacture. The impact can be indirectly seen in the addition of stocks. The future availability of flows for reuse or recovery could be indirectly approximated based on the "product Lifespan" and throughput matrix implemented in the UMAn methodology of Rosado et al [39]. These characteristics aim at estimating the number of products or materials, per product type, becoming obsolete each year and, therefore, which cannot be reused.

Based on the results of the estimation of flows through these adapted EW-MFA indicators, Mayer et al. developed a CE assessment framework divided into two parts: the scale indicators measuring the dimension of the urban metabolism and Circularity indicators giving information on the degree of circularity of the system and its efficiency [43]. Adaptations of this methodology have been made within the Cityloop project to consider the constraints and specificities of the urban scale, like waste treatment and recycling that do not necessarily occur within the geographical city boundaries [38].

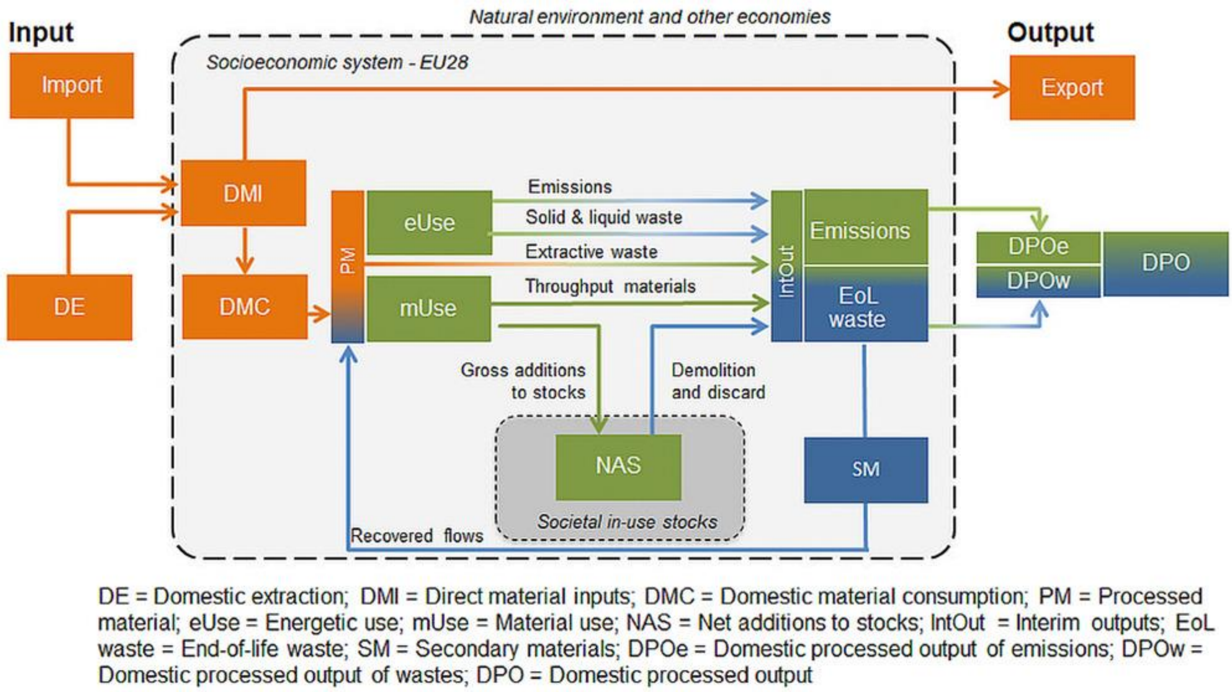

Figure 4: Circularity assessment framework based on adapted EW-MFA methodology as proposed by Mayer et al.[43]

Energy flow assessment: Flow analysis methods also include energy flow assessment methods. In their review on flow analysis methods, Hoekmann and Bellstedt [32] differentiate three ways to account for energy flows: the energy accounting relying on the quantification of specific energy flows at building level, the energy balance, which considers the energy used by the physical infrastructures within the city, and the energy flows analysis that considers the bigger picture and accounts for all energy uses within the city.

Material Stock Analysis: Material stock analysis is particularly relevant when dealing with materials used in the built environment. There are two main approaches to obtain the material stock of a city or neighbourhood:

<u>The top-down approach:</u> The top-down approach quantifies stock as the difference between inflows and outflows calculated from year-to-year. This approach is used in many but fails to provide a high spatial resolution for the material stocks [45].

<u>The bottom-up approach:</u> As described by Tanikawa et al. [46], the bottom-up approach consists in clustering the existing stock per categories: function, form, year of construction, and

use material intensities for each identified category to account for the material stock. The total material stock is then calculated based on Equation 1.

$$MS_{m,i,t} = INV_{i,t} * MI_{m,i,t}$$

Where MS is the material stock of material *m*, for type *i* measured in year *t*. INV is the inventory of item of type *i* in year *t* and MI is the material intensity of material *m* in one unit structure type *i* [46].

The bottom-up stock accounting methodology can be divided into four steps as highlighted in the EU **H2020 project City Loops** within the urban circularity assessment methodology [38]:

(1) Find locations, land use and floor areas of buildings

(2) Gather building typologies (depending on the scope of the study, this also can entail roads and pipes typologies)

(3) Determine building typology's material intensity: material intensities are calculated from building documentations, such as building plans, building techniques or quantity takeoffs

(4) Calculate material stock and spatialize it.

Numerous examples of bottom-up MFA can be found in the literature. For instance, the urban material stock model developed by Lanau et al. for the city of Odense in Denmark quantifies the amount and spatial distribution of material stocks for 46 construction material types for different categories of buildings (the archetypes are based on building use, year of construction and number of floors), roads (the archetypes are based on traffic class, width, and length), and pipes (the archetypes are based on length, line type and nominal pressure) [47]. A similar bottom-up stock approach for buildings, roads network, and pipes has been performed by Gontia et al. in the living-lab city Gothenburg [48], the archetypes and hypotheses used are detailed in section 4.2.1. Examples of similar spatialized bottom-up approach applied for flows accounting can be found in the work of Augiseau and Kim for the metropolitan area of Paris [27] or the analysis performed by CiteSource and NeoEco for the living-lab city Rennes, detailed in section 4.1.1.

2.2.2 Secondary materials stocks and flows mapping

Further analysis of the local context is required to estimate the secondary materials inflows and outflows based on construction material stocks and flows models. In a review of the role of anthropogenic resource classification in supporting the transition to a circular economy, Winterstetter et al. [49] identify three challenges faced by secondary resources: resource potential, recovery potential, and utilization potential, as depicted in Figure 5and elaborated underneath.

Figure 5: Challenges faced* by *anthropogenic resources as proposed by Hoekman and Bellstedt [32]

- The resource potential includes the need for more information regarding the geographical and temporal availability of secondary materials. The secondary resource potential is estimated by calculating outflows within material flow analysis. The geographical stocks of material can be mapped using a combination of bottom-up material stocks analysis and local GIS data, as performed within the ULL cities included in the CREATE project; details on these modelling approaches are provided in section 4. The estimation of the temporal availability of the secondary resources varies depending on the model. A first approach consists in estimating the demolition year based on the construction year and an average lifetime for each type of infrastructure, as performed for Gothenburg [50] and recommended by the environmental assessment of construction work developed in the Netherlands [51]. Alternatively, scenarios can be developed to consider the influence of local policies, as in Vienna [7,52] or Rennes [53]. More complex approaches, such as the definition of a System Dynamics model, have also been developed to evaluate the temporal distribution of material outflows: Zhou et al.

developed a system dynamics model for building stock turnover and the associated energy performance of buildings [54]. The demolition considerations include a hazard rate of demolition for each building age category. The retrofit flows are calculated based on an age-specific retrofit rate controlled by a default retrofit profile and a retrofit parameter based on local policy scenarios. Energy demand reduction outflows are calculated based on the number of retrofitted buildings and the energy intensity reduction achieved by retrofit based on a specific retrofit depth, describing the extent to which the energy intensity of existing buildings can be improved.

- The recovery and utilization potentials include technical limitations linked to using secondary materials or fuels. This includes differences in quality and physical properties between secondary and virgin raw materials. To account for these differences, the national guidelines to assess the environmental impact of buildings in the Netherlands [51] indicates that the secondary material or secondary fuel flows need to be expressed in raw material equivalent. This enables the correct environmental impact accounting within the life-cycle assessment. It includes the secondary material and fuels used as inflows for the production phase and the materials available for recycling as output flows of the dismantlement and processing phases. The raw material equivalent can be estimated qualitatively or quantitatively based on the physical properties of the secondary materials. In the case of reusing products or secondary materials, a quality factor based on the decrease in the technical quality of the material can be estimated and used to estimate the net flows of material that can be reused in the end-of-life phase. The recovery potential is also highly dependent on the technical characteristics of local recycling and reusing processes and facilities. To evaluate the availability of local facilities and estimate reusing and recycling material outflows, a mapping of the local recycling and reusing actors and an analysis of the readiness of the local supply chain have been performed in Rennes Métropole for each type of construction material. The results have been used to develop short, mid, and long-term scenarios for recycling capacity [1]. An analysis of stocks and current and future inflows and outflows of construction materials in the urban area and 6 urban projects has also been performed. Alternatively, assumptions can be made based on available data: in Vienna, the amount of recycled and reusable mineral construction materials has been estimated based on available yearly reuse and recycling rates at the country level [17]. Besides, the Dutch environmental impact assessment methodology indicates that any additional material or energy used for the end-of-life processes must be accounted for in the material flow analysis and the LCA model. Finally, both the recovery potential, influencing the outflow of recycled and reusable material, and the utilization potential linked to the inflow of secondary material in the production phase are not only dependent on technical factors. Existing regulatory or governance frameworks, economic constraints, or social acceptance [49] also influence the secondary material flows. Analyses of the existing legal frameworks in living-lab cities and necessary regulations to support the implementation of CE strategies are presented in deliverable 2.1. Governance frameworks are analysed within the scope of work package 4.

2.3 Stocks and flows modelling data sources and types

The availability of data on material stocks and flows and their localization at the local level is crucial for the definition tailored policies and evaluating the circular economy potential of a given location. In the bottom-up approach, the material stock data can be spatialized using GIS models of the locations. GIS files should contain explicit information on the building (gross floor area in m^2, the height and number of stories) or archetypical information (the building use and/or the construction type, the date of construction and if available the last date of renovation of the building). The stocks can then be estimated based on the definition of archetypes as detailed above. This methodology has been applied in many studies dealing with urban stocks and flows. In Gothenburg, a clustering algorithm was used to identify material availability at the neighbourhood level and derive neighbourhood types [48]. The GIS data of a location are extracted from the local cadastre, if available. If the data are not available, open-source tools such as OpenStreetMap can provide information on the existing infrastructures. However, bottom-up material flow analysis using building archetypes, leads to a loss of detail regarding the building composition and can lead to uncertainties when applying the material flows assessment method. Data collection methodologies based on computer vision tools could be used to tackle this uncertainty and enable the assessment of building component stocks, most suitable to assess the reuse of circular economy strategies. Arbabi et al. show, in a case study for the city of Sheffield, that a combination of different capture technologies (LIDAR, Visual, Thermal, and Hyperspectral) allows to account for the quantity and the dimensions of materials and components ,*e.g.*, doors and windows of a building [55] . Hyperspectral data appear to be particularly suitable to account for building stocks, when combined with facade segmentation models, as shown by Dai et al. [56].

I lack of data at the local level, larger-scale data can be downscaled to assess the urban stocks. There are multiple methodologies to downscale data to derive local models. For example, Bianchi et al. [57] use an econometric model to downscale European data to country-specific data.

For secondary materials, the Opalis project [58] provides an extensive overview on current practices in construction material reclamation and reuse in Europe and their related challenges. Within this ongoing project, markets for secondary construction materials were explored and a registry of active vendors for reclaimed materials in the participating countries (Belgium, France and Netherlands) is provided [59]. Additionally, the project team compiled a comprehensive guide on reusable construction materials, called material sheets. These materials sheets provide valuable and detailed insights in the reusability of construction components ranging from interior equipment such as doors or sanitary components to construction materials like bricks, steel beams or cement [18]. The insights include descriptions on the necessary steps for the reclamation of materials as well as the requirements on material properties. The material sheets do not only provide qualitative descriptions, but also quantitative comparisons between reclaimed materials and comparable new materials with regards to market price and climate impact. This makes the Opalis project a valuable source of information, not only in the conduction of LCA, but also throughout the design phases of construction projects in general.

2.4 Life-cycle assessment to support reuse and recycling of secondary materials

The analysis of material and energy stocks and flows can provide valuable insights into the consumption of primary and secondary resources. However, resource depletion is only one aspect of the environmental implications of urban construction. For example, a life-cycle assessment (LCA) study conducted by Lachat et al. demonstrated that circular economy strategies like using recycled aggregates from demolition and construction waste instead of virgin aggregates in concrete production do not always reduce environmental impacts, as the case-specific context is relevant. While the use of non-virgin materials may conserve primary resources, it does not necessarily reduce other environmental implications such as global warming potential [60]. A coupling between MFA and LCA can provide information on the amount and types of material flows available, and the environmental implications associated with their use. This approach can generate insights regarding the environmental performance of circular economy strategies in urban construction. This coupling also addresses the limitation of material stocks and flows accounting methodologies in terms of environmental impact assessment. Such a coupling is further suggested in recent literature on the topic [61].

The field of life-cycle assessment for buildings and infrastructure encompasses a variety of calculation and certification methods, each emphasizing different aspects of environmental impacts, *e.g.*, weighted scores (Ökoindex 3) [62] or conversions of impacts to €/m² as in the Netherlands [51]. Additionally, existing calculation methods can also cover different scopes of life-cycles, *e.g.*, cradle to gate, cradle to grave, or cradle to cradle. In some cases, this diversity impedes the setup of comparable baselines for embodied emissions in buildings across EU member states, as found in [63] . Most certification schemes, however, are based on the EU standards EN 15804+A2 and EN 15978, which provide a standard for the calculation of building material impacts and buildings themselves. The following subchapter introduces the stages of use defined in EN 15804+A2 with relation to the assessment of circular building materials.

2.4.1 Building material environmental product declaration (EPDs) in EN 15804+A2

Construction products offered on EU-market can provide eco-labels in form of environmental product declarations (EPDs). EPDs follow the standard EN 15804+A2 [64], which demands a set of environmental impact indicators, and describes methods to calculate them. It is important to note that EPDs are eco-lables of the category III and therefore do not provide a comparative rating of construction products. They are rather a standard-based source of information on environmental implications, that can be used in other eco-rating systems.

EN15804+A2 divides the life-cycle of construction products into four main modules, which comprise production, construction, usage, and end-of-life. These stages are further subdivided and are illustrated in Figure 6. Within those life-cycle stages of a product, EN 15804 demands the accounting for related environmental impacts within five impact groups. These impact groups include indicators derived from LCA and comprise energy indicators, material and waste indicators, flows leaving the system, and more [65]. The addition of EN15804+A2 introduced a further differentiated assessment of climate change impact indicators, now distinguishing between impacts originating from fossil sources, biogenic sources, and land use and land use changes. This allows the identification of impact hotspots throughout the life-cycle of a product. Additionally, this modular approach allows for the modeling of secondary, *i.e.*, circular construction materials and products.

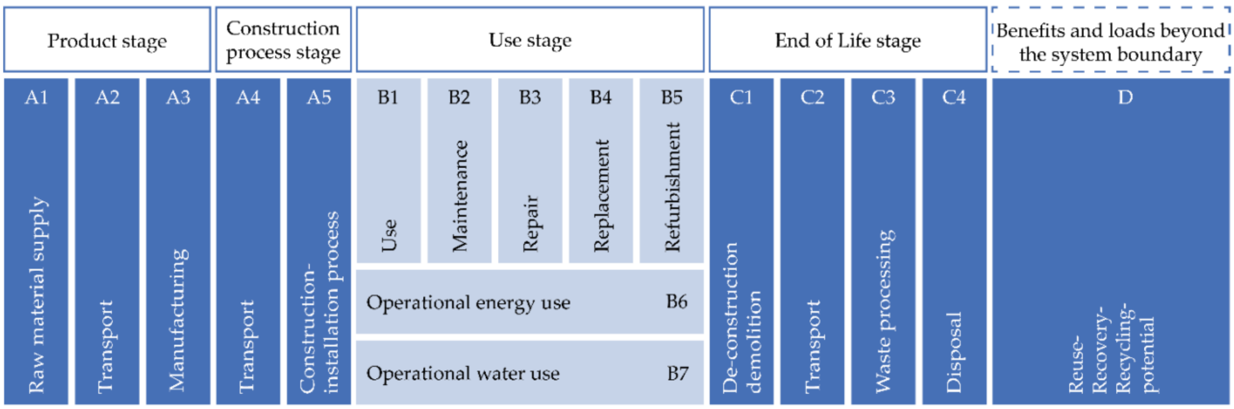

Figure 6 Life-cycle stages of construction products according to EN 15804 [66]

To consider the reuse and recycling of building materials, requirements to allocate the environmental burden of the different material life-cycle-stages to the primary or secondary products are developed. In EN 15804, the allocation of environmental impacts is based on the cut-off methodology, which follows the polluter pays principle [67]. Environmental impacts of reclaimed and reused secondary materials are covered in module D "Benefits and loads beyond the system boundary". Hence, the "first" and "second" life of construction materials are considered separately. This implies that the application of circular economy principles influences life-cycle impacts of primary products (C4 and potentially C2), as well as reclaimed / recycled secondary products (A1 to A4 depending on individual case). Figure 7 provides a comparison of the impacts of recycling, reuse, and classical approaches the to the usage of construction materials with regards to their life-cycle impacts. It highlights the benefits of reuse, especially *in situ* over recycling and linear economy.

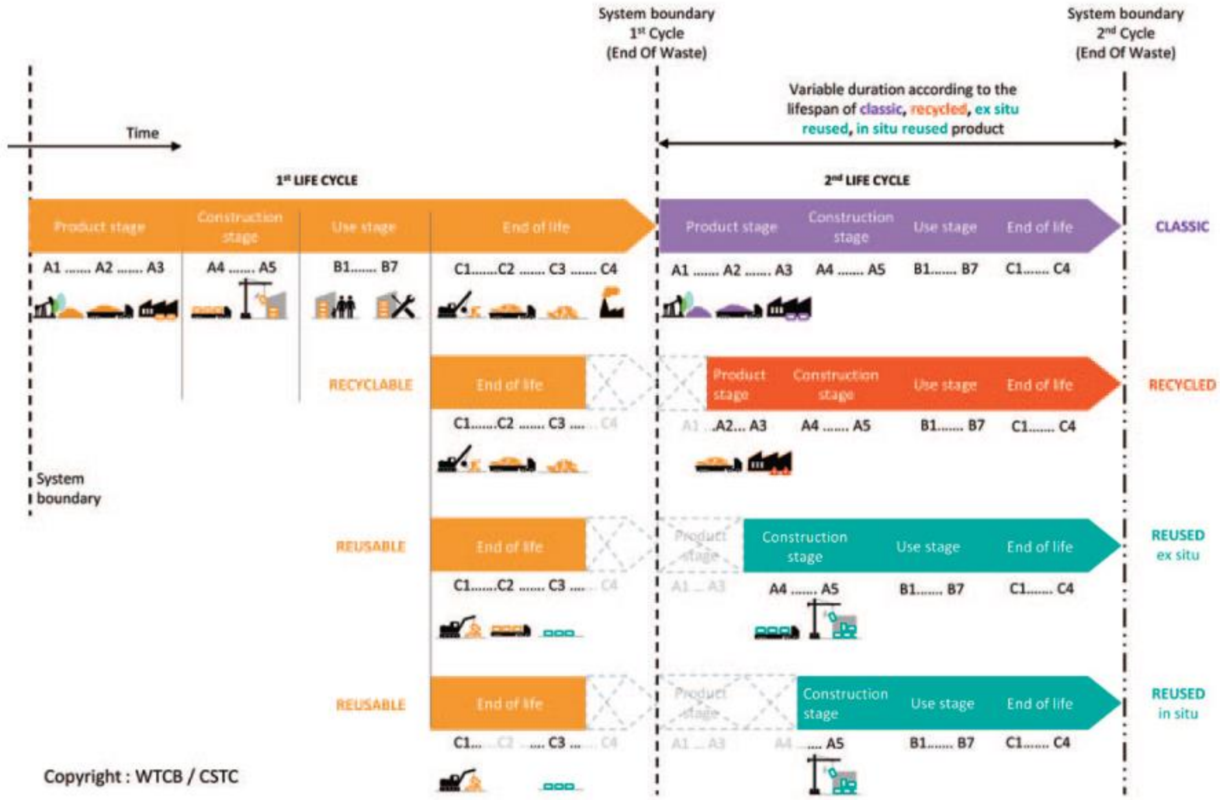

Figure 7: Impact of circular economy strategies on life-cycle stages of construction materials. Source: [68]

2.4.2 Limitation of life-cycle assessment methodologies to evaluate the impact of circular economy strategies

The literature review highlights limits of the current life-cycle assessment framework to fully evaluate the environmental impact of circular economy strategies, *i.e.*, recycling and reuse in the scope of CREATE).

The modelling of the end-of-life scenarios (EoL) with the current LCA frameworks does not capture the full environmental impact of circular economy strategies. As highlighted by Lei et al. [8], the current European standard for LCA in buildings EN 15978 does not include waste flows throughout the entire life-cycle of the building and excludes the demolition impact of added or reused components. To overcome these challenges, the system boundaries of LCA should be extended to include waste flows during the use phase and the implications of the demolition phase. These impacts can be divided into two categories: embodied impacts and operational impacts. Embodied impacts are divided into three sections: initial embodied impacts during the production and construction stages, the recurrent embodied impacts, including the impacts of repaired, replaced, and refurbished materials, and the demolition impacts, including reuse and recovery of materials.

The second limitation is the modelling of multiple cycles for CE strategies. This requires the choice of an allocation method. Eberhardt et al. [69] analysed different environmental allocation methods for building materials and compared them through a case-study. Results show that if the cut-off approach from the EN 15804 framework works well to assess circular design in a linear setting, however, it has shortcomings when it comes to assessing circular economy in a multi-cycle analysis. Different allocation methods are presented in the literature such as APOS (allocation at the point of substitution) used in the eco-invent data base [67] or the CFF (Circular footprint Formula) developed by the European Commission, and assessed by Eberhardt et al. [69]. The choice of the environmental impact allocation method can highly impact LCA results. For this reason, Lei et al. recommend to perform a sensitivity analysis and compare the results with different allocation methods [8].

Another limitation of classic building LCA for CE strategies assessment is the lack of temporal consideration, ignoring the diverse life spans of building components and materials, which further complicated in the context of CE, as highlighted by the United Kingdom Green Building Council (UKGBC). Besides, current LCA methodologies are a static models [8,34] and do not consider dynamic changes in technological progress, resource availability, or occupancy behaviour. Dynamic LCA models (DLCA) have been developed [70], but their uncertainties remain too high to be used in a CE context.

The fourth limitation of currently applied LCA methodologies is a lack of holistic performance assessment. As highlighted by Pomponi and Moncaster [71], and Eberhardt et al. [69], circular economy assessments in the built environment should include both environmental performance and technological, economic, societal, governmental, and behavioural aspects.

Finally, the last limitation highlighted is the lack of local data. Both LCA and MFA require detailed data at material and component levels. However, as highlighted by Hossain et al. [72], there is a lack of local data, and most LCAs are based on outdated or non-specific Eco Invent data. As circumstances can differ greatly depending on the building use, type, and region, the set of data used can have a significant impact on the LCA results. Several initiatives, such as BIM-based methodologies [73] and material passports developed within the European project BAMB [74] are being developed to address this data issue.

2.4.3 Modelling tools and databases for circular economy in construction and life-cycle assessment

The LCA of the usage of secondary materials in urban construction is crucial for the validation of the advantageousness of circular economy concepts over business-as-usual linear economy approaches to urban construction. While being a nascent field in the discipline of LCA due to the relative novelty circular economy concepts in urban construction, literature and available tools and databases already provide approaches towards LCA for secondary construction materials in urban construction, some of which are presented and discussed in the following.

2.4.3.1 Data soures for life-cycle assessment in the construction sector

To accurately evaluate the environmental impacts of circular economy strategies in urban construction, it is essential to determine the environmental impact of each product utilized during the building or infrastructure construction. EPDs are an essential tool for obtaining detailed information regarding the environmental impact of construction materials at a country or regional level. These declarations can be provided directly by manufacturers, or in national databases ,*e.g.*, INIES in France or Milieu Database in the Netherlands. They provide detailed data concerning the environmental impact of each material used in each stage of the life-cycle, as outlined in the EN15804+A2 standard for EPDs. The use of EPDs in life-cycle assessments (LCAs) offers the advantage of providing precise and comprehensive information on environmental impacts, thereby enabling policymakers and other stakeholders to make informed decisions. Nevertheless, it is essential to note that EPDs are limited to finished products, and do not consider the environmental impact of intermediary construction products.

Global LCA databases,*e.g.*, Ecoinvent, Gabi are also available, providing valuable information on construction products, energy, and transport environmental data. Although these databases may not provide as accurate information on the local environmental impact of finished products as EPDs, they offer significant benefits in terms of the provision of data on intermediary construction products. Furthermore, the availability of such data facilitates the identification of the environmental impact hotspots within the supply chain, thereby enabling more effective environmental management strategies.

Table 1 provides a summary of the databases relevant for the ULLs of CREATE, outlining their scale, country specificity, and accessibility of data. In the subsequent project tasks, a data selection methodology will be developed based on data quality criteria, including geographical, technological, and temporal representativeness. In most cases, the combination of local EPDs data with Ecoinvent data for the missing information appears to be appropriate.

Additionally, the technological mapping of the material and energy supply chain for the identified urban living labs will be conducted and presented in deliverable 5.2.

Table 1: Reviewed LCA databases for construction materials

Name	Geographical coverage	Sectoral coverage	Temporal coverage	Environmental indicators	Data openly available	Compatibility with LCA software
Ecoinvent [67]	Worldwide (different scales: worldwide, European or country scale data)	Multiple (including construction material), including subprocesses	Yearly updates	Depends on the impact assessment method selected (including indicators of EN15804+A2)	NO (license fees)	+++
Gabi [75]	Worldwide (different scales: worldwide, European or country scale data)	Multiple (including construction materials), including subprocesses	Yearly updates	Depends on the impact assessment method selected (including indicators of EN15804+A2)	NO (license fees)	++
INIES [76]	France	Construction materials EPDs	Regular updates (<3years for each product)	Indicators of EN15804+A2	YES (consultation), fees for download	+++
Base Carbone (ADEME) [77]	France	Multiple (low coverage of construction materials)	Yearly updates	GHG emissions	YES	+

Nationale MilieuDatabase [78]	The Netherlands	Construction materials EPDs	Regular updates (<5years for each product)	Indicators of EN15804+A2	NO (license fees)	+++
Boverket [79]	Sweden	Construction materials	Yearly updates	GHG emissions	YES	+
Ökobaudat [80]	Germany	Construction materials EPDs	Last update 2021	Indicators of EN15804+A2	YES	+++
Baubook [81]	Austria	Construction materials EPDs	Last update 2023	Indicators of EN15804+A2	YES	+

2.4.3.2 LCA software

The assessment of the life-cycle environmental impacts of construction materials involved in different circular economy strategies is facilitated by LCA software tools. In this regard, a review of existing LCA software tools was conducted, and a comparison of the tools was carried out based on various criteria. One of the significant criteria used in comparing the tools was the field of application, which determines the tool's scope. The tool scope is categorized into three levels: general, building level, and urban areas/districts level. The licence costs of the tools were also reviewed. The databases included in the tools were also compared as they are vital in providing relevant data for LCA calculations. The available allocation methods in the tools were assessed to consider the multi-cycles of circular economy strategies. The included environmental characterization methods were also reviewed to ensure the coverage of the three main indicators evaluated in CREATE, being resource depletion, GHG emissions, and energy consumption. Finally, additional features were evaluated to determine if the tool provided any added value for the project.

Overall, the review provided valuable insights into the available LCA software tools and their capabilities. The following sections describe examples of general, building specific and urban project LCA software. It is worth noting that the list of reviewed software tools is non-exhaustive and limited to the most used software identified in the literature or with relevant link with the CREATE ULLs.

2.4.3.2.1 Example of general LCA software

- OpenLCA

OpenLCA is an open-source modelling framework for LCA developed by GreenDelta. It is one of the worlds mostly used license-free LCA tools [82], offers a graphical user interface, and is continuously developed and improved. It is freely available under the Mozilla Public License, MPL 2.0 and offers integration of free databases and commercial databases like ecoinvent or GaBi. Databases can be integrated through standards like ILCD or EcoSpold, or imported via the "OpenLCA Nexus" [83]. Concerning life-cycle impact assessment methods, OpenLCA currently offers 43 different ones, including ReCipe, EN15804+A2, and CML. The open-source approach, however, also allows for customized assessment methods.

- SimaPro

SimaPro is a LCA software used in more than 80 countries. The software is designed to enable the environmental assessment of every product type. Therefore, more than 15 free and paid databases covering different geographical and functional scopes are available to perform the inventory analysis. Examples of the included databases (called libraries in SimaPro) are EcoInvent, Agri-footprint or the US Life-Cycle Inventory database. Besides, the software includes more than thirty different environmental impact characterization methods. SimaPro users can choose the relevant characterization method for their analysis depending on their location and the type of environmental impact assessed. In SimaPro, the allocation method used to perform the life-cycle assessment of recycled or recycling materials depends on the selected database and is indicated in the definition of inputs during the inventory analysis [84].

- Gabi

The commercial software tool Gabi, developed by Sphera Solutions GmbH, offers both a modelling software tool for LCA, and an individually curated database that spans a wide range of industries, *e.g.*, agriculture, energy & utilities, metals & mining, and services. The database is commonly used for the creation of EPDs following EN15804+A2 [85]. Additionally, the software tool integrates other widely used LCA databases like ecoinvent to provide a reliable and extensive source of LCA data. While the modelling tool is advertised specifically for the consumer products and industry goods [86], it also offers the possibility for building LCA due its flexible application of impact assessment methodologies, including for example ReCiPe, TRACI, or CML. Besides, GaBi offers the possibility of life-cycle cost accounting, given the availability of corresponding data.

2.4.3.2.2 Examples of building specific LCA software

- One Click LCA

One Click LCA presents itself as user-friendly software tool to conduct building and infrastructure design studies using LCA [87]. As the tool itself is also widely used to generate EPDs for construction materials, One Click LCA integrates an extensive database of EPDs that is constantly updated. Besides individual EPDs, the database also contains generic data. These generic data are either integrated directly from national datasets or from external sources like ecoinvent. Additionally, generic datasets are provided by forming mean environmental impact factors over product groups and regions, making use of the extensive EPD database. To further account for individual contexts, the tool also allows for the adjustment of related transport kilometers and underlying electricity mixes. To account for circularity and reuse of construction materials, the tool on the one hand integrates recycled materials in its database and on the other hand allows the consideration of various options in a material's end-of-life, *e.g.*, landfilling, reusing, crushing.

Depending on the requirements and available license, One Click LCA offers a wide set of calculation methods for environmental impacts construction projects, *e.g.*, EN 15978 for buildings or PAS 2080 for infrastructure.

- TOTEM tool

The TOTEM tool (Tool to Optimize the Total Environmental impact of Materials) allows the modelling of buildings and their related life-cycle impacts. The tool considers environmental impacts and energy usage resulting from life-cycle of building components themselves, and also provides a simplified modelling approach to operational energy use in buildings resulting from heating energy demand, therefore providing a holistic approach to the life-cycle assessment of buildings. TOTEM integrates localized EPD databases (Belgium and Netherlands) and generic LCA data from databases like ecoinvent to provide an extensive dataset of construction components, comprising 1035 entries as of June 2022. Due to the lack of standardized and documented secondary materials and EPDs for secondary approaches, TOTEM applies a pragmatical concept to consider secondary construction materials for which no specific LCA data is available. Construction components can be considered in 5 different statuses regarding their circularity (new, existing, reused *ex situ*, reused *in situ*, and demolished), which results in the exclusion of specific life-cycle stages, *e.g.*, raw material supply or transport in the overall LCA. By applying this logic, and by using available EPDs for new components that are as close as possible to the installed secondary ones, an LCA is performed for buildings that use secondary materials, even if LCA data on these secondary materials is limited. Currently, the tool's library focuses on EPDs for components from the original project participating countries, however, the database can be extended upon individual request and availability of data [31].

- EQUER:

The research institute of systems energy efficiency in Mines ParisTech has developed a life-cycle assessment software for the purpose of evaluating the environmental impact of buildings in compliance with the building regulations and certification in France (RE2020 and E+C-) [88]. The software enables the calculation of 12 environmental indicators including global warming, resource depletion and energy consumption using the ecoInvent database. The software, like OneClickLCA, can model the building from scratch or based on a digital model imported into the system. However, it requires accurate information on the building and does not allow modeling at the material level. In addition, it is important to note that, although a free demo version of the software is available, the full version of the software requires a valid license. Furthermore, a new version of the software has been introduced for district-scale assessments.

2.4.3.2.3 Examples of urban projects LCA software

- EvalMetab

The "Chaire Economie Circulaire et metabolisme Urbain" at the Gustave Eiffel university has developed a software tool called EvalMetab [89], which evaluates the metabolism of urban projects and assess recycling strategies. This software considers both the demolition of existing buildings and the construction of new ones. The estimation of material quantities is based on a bottom-up stocks methodology, which identifies building archetypes and associated material intensities. Scenarios can be created and compared based on greenhouse gas emissions and costs for both recycling rates and transport logistics. Regarding recycling rates, the software provides the option to choose between different strategies such as maximum achievable recycling rate, recommended recycling rate, or user-defined recycling rate. The logistics scenarios allow for varying the transport distances and modes for construction materials.

- UrbanPrint

The software, Urbanprint, has been jointly developed by Efficacity and CSTB. It is built on the "Methode Quartier Energie Carbone" framework established by the French environmental agency ADEME [90]. The primary features of Urbanprint comprise the evaluation of environmental performance at the district level, mainly focusing on energy and carbon, while also considering various other environmental impacts such as construction products, water, waste, and mobility based on EN15804+A2. Urbanprint facilitates the comparison of different scenarios and evaluates the potential actions for reducing environmental impacts. The primary data sources for Urbanprint include ecoinvent and INIES databases.

2.4.3.2.4 Comparison table of the software analyzed

Error! Reference source not found. summarizes the comparison of the LCA software described in the previous section based on the following criteria: scope of the LCA performed (general LCA software, building specific software or urban project specific software), the databases included, the allocation method used (if applicable), the characterisation method included, the user friendliness and special features useful within the scope of CREATE.

A techno-economic mapping of the flows and processes of materials and energy involved in a business-as-usual approach and for circular economy approaches will be performed for each case-study area with identified databases. This mapping will serve as the basis for a life-cycle assessment inventory. The review of the different databases presented in Table 1 and LCA software summarized in **Error! Reference source not found.** led to the choice of using local or regional EPDs databases and the global database ecoInvent [67]. The life-cycle assessment model will be developed using the open source LCA software OpenLCA. The analysis of different circular economy scenarios' environmental impacts will be presented in deliverable 5.3, while deliverable 5.2 will provide details on the mapping and generated inventory.

Table 2 LCA software comparison

Type	Name	Software licence	DB included	Allocation method	Characterisation method included / Environmental assessment	User friendliness	Special features
General software	SimaPro	Yes	eco-invent, gabi	Ecoinvent APOS	CML,ReCiPe, EN15804 + A2	+	-
	OpenLCA	No	eco-invent (not free), gabi, probas.	Ecoinvent APOS	CML,ReCiPe, EN15804 + A2	+	-
	Gabi	Yes	gabi	Depending on the database	CML,ReCiPe, EN15804 + A2	+	Calculation of material circularity indicator
Building specific software	OneClick LCA	Yes	oneclick LCA DB + EPDs	EN15804 or market based	CML,EN15804 + A2, and others	++	Infrastructure LCA, LCC, circularity assessment, BIM integration
	Totem	No	EPDs + Ecoinvent + possibilty to add material	Market based, depends on the material considered	CML,EN15804 + A2	++	Circularity assessment, 3D models of the building
	Equer	Yes	Ecoinvent	Not relevant	EN15804+A2	++	3D models of the building

Type	Name	Software licence	DB included	Allocation method	Characterisation method included / Environmental assessment	User friendliness	Special features
Urban project level software	UrbanPrint	Yes	Ecoinvent, INIES	Not relevant	Methode Quartier Energie Carbone	++	Comparison of scenarios and evaluation of different actions levers
	EvalMetab	No	Ecoinvent	Not relevant	GHG emissions	+	Comparison of costs for different scenarios.

3 DECISION SUPPORT BEST PRACTICES

To reap the benefits of circular economy in the construction sector, new governance arrangements need to be discussed and tested. Therefore, CREATE puts a strong focus on this aspect. WP 4 directly aims to facilitate the use of decision-making support developed in WP 3 and WP 5, stimulating the circular use of construction materials. This is done by identifying current best practices and conducting workshops across the international partners. Additionally, WP 6 deals with the processing of lesson learned and the dissemination of results obtained in the living lab cities to the fellow cities. The following section provides an overview on current activities within partners of the consortium and on the broader European scale in similar research projects.

3.1 Workshop Vienna / DoTank

To better understand the current advance and needs of cities towards circular construction and establish a relation to local stakeholders in Vienna, “DoTank Circular City Wien 2020-2030 (DTCC30)” (DTCC30) [91] has been introduced to the project. DTCC30 is a cross-magistrate program of the city of Vienna that was established to support circular economy in the built environment strategically and in operation. Besides the recent involvement in CREATE, DTCC30 also participates in the Horizon 2020 project City Loops and therefore serves as valuable partner in the process of identifying circular economy needs and the dissemination of project results.

On June 3rd, DTCC30 held a symposium about circular construction in Vienna with invited speakers and guest from the city government and construction and demolition industry. AIT attended in the setting of CREATE, which provided valuable insights into the challenges of circular economy in construction and ongoing policy debates. Initial inputs by real estate developers, construction companies and consultancies were followed by workshops on the topics of buildings, infrastructure, socio economy, and urban planning. The workshops' key findings included that the successful implementation of circular economy in the construction sector will require an intensive learning process that involves the "unlearning" of linear economy to allow the implementation of new concepts that link the beginnings and ends of life-cycles. Furthermore, cross-sector collaboration will be required to initiate this paradigm shift. Hence, innovative actions must target new ways of collaboration between sectors. Finally, circular economy and the use of secondary materials must not be an end in themselves. Therefore, circular economy should focus on thewaste mitigation, which means to prolong the use of buildings and infrastructure as long as possible, and to always contextualize construction projects in their respective quarters and districts, rather than assessing their circularity on their own. [92].

DTCC30 will take part in the co-dissemination events of WP6. Their participation and contributions will both enrich the process of finding ways of embedding the findings of the project in governmental processes and support the city of Vienna in the implementation of circular economy through the knowledge transfer from project results.

3.2 Other EU projects

As the matter of resource depletion becomes more pressing, the topic of circular economy comes more and more into focus research efforts. Hence, CREATE stands among other EU funded research projects that aim to foster circularity in cities. To set following sections process the findings of these related research projects and contextualize CREATE within the framework of European research on circular economy in urban construction.

3.2.1 CityLoops

Being implemented within the framework of Horizon 2020, CityLoops counts among the biggest research efforts towards circular economy in urban construction in Europe. The main implementations of the project involve the cities of Apeldoorn, Bodo, Hoje-Taastrup, Mikkeli, Porto, Roskilde, and Seville. Although construction materials are one of the focus points of CityLoops, the project went beyond this aspect within its understanding of circularity in cities. Specifically, the project team developed a circularity indicator set that also encompasses for example energy, mobility, water management, and employment aspects across 94 indicators [93]. The main results of the project include the identification of a lack of data on material stocks and flows on the city level, highlighting the importance of the "assessor" of circularity, as this influenced the process of data collection in the analysis. Furthermore, the aspect of capacity building was highlighted as challenging due to the diverse governance arrangements found in each city. Another interesting outcome of the project was the encountered prioritization of establishing a baseline of circularity in the city for city administrations. Many cities focused on the implementation of circular economy through demonstration projects, rather than systematically developing strategies based on sound material stock and flow analyses [94].

Furthermore, a review of urban material flows and stocks accounting methods was conducted throughout the project. The review did not only cover construction materials, but also provides a comprehensive outline and assessment of accounting methodologies for urban material flows and stocks. The work suggests that material stock and flow analyses should be coupled with LCA to fully tap the potential for knowledge gain provided by material stock and flow analyses. The local availability of data and experience of local stakeholders have been found to be decisive for the applicability of certain methods. Hence, the review proposes to let data availability drive the choice of assessment methods and not vice versa [32]. These findings are in line with the modelling approaches and project structures proposed in CREATE. The LCA conducted in WP 5 builds on the material stock and flow models developed in WPs 2 and 3 in a similar manner as suggested and reviewed in [32]. It is therefore evident that the European research project landscape provides mutual benefits in the field of circular cities and their assessment.

3.2.2 Bamb

The BAMB (Buildings as Material Banks) project is an EU H2020 initiative aiming at accelerating the shift toward a circular economy in the building sector. One of the main objectives of the project is the development of a Material Passport Platform integrating BIM (building information modelling) [95]. The material passport aims at supporting circular construction by providing relevant data at material and building level for circular economy strategies such as the physical, chemical, and biological properties, the design and production specificities, the disassembly and reversibility properties or the reuse and recycling potential. The BAMB database of material passport can be used to fill-up the data gap for the assessment of circular buildings. Another outcome of BAMB is the Circular Building Assessment Prototype presented in Figure 8that calculates circular economy indicators for different building design and material choices [96].

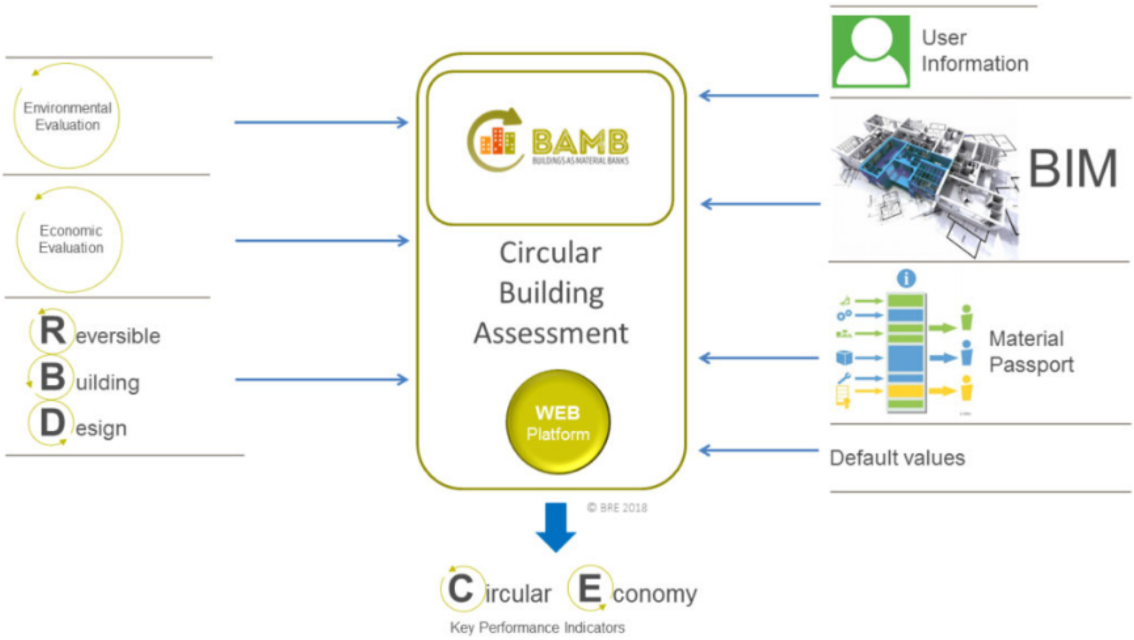

Figure 8: Circular building assessment prototype [57]

3.2.3 Houseful

The Houseful project is a European initiative to shift towards a circular economy in the building sectors. This Horizon 2020 funded project started in 2018 and is running until October 2022. The goal of this project is to implement circular building solutions in four demo sites: Els Mestres (Sabadel, Spain), Sant Quirze del Vallès (Spain), Cambium community Center (Fehring, Austria) and Donaufelder Strasse 115 (Vienna, Austria). Specifically, the two main objectives of this project were to develop a methodology to quantify the degree of circularity of a building at different stages of its life-cycle, and to assess the potential environmental and socioeconomic impacts of the demonstrated circular strategies. To evaluate the different circular economy scenarios, demo sites have been described through a BIM model and material passports [97]. The material passports for each building are generated through the web app "Madaster" and contain information about the quality and the origins of the material and give information on the circularity and financial value of the buildings [98]. A set of KPIs to measure the circularity of a building has also been developed within the Houseful project. The proposed framework includes 17 indicators spanning for example from life-cycle energy consumption to materials circularity indicators and life-cycle costing [99].

4 STOCKS AND FLOWS MODELS OF THE LIVING LABS

The available material stock and flow data in the three living lab municipalities is derived from existing literature and the results of WP2. The following chapter discusses the situation in the three living lab cities and establishes the basis for the subsequent LCA of circular construction scenarios, which will be presented in D5.3. Table 3 describes and compares the methodology and scope of the existing stocks and flows for each city involved in CREATE.

Table 3 Comparison of in-use stocks and flows model of the living-labs cities				
Characteristics of the study [100]	**Rennes**	**Gothenburg**	**Nijmegen**	**Vienna**
Spatial boundaries and level of resolution	Buildings and road infrastructure (stocks + flows)	Stocks: Buildings (Residential and non-residential), Road's infrastructures (Bike lines and roads), Pipes (drinking water and wastewater) Flows: Residential buildings (MF+ SF)	Buildings and road infrastructures (flows)	Buildings and transport infrastructures. (stocks + flows)
Temporal scope	2017-2019: retrospective 2020-2030: prospective	Stocks: 1900-2019 Flows: 1900-2100	Yearly flows (for the year 2016)	(Buildings) 1990 – 2015: Retrospective 2015 – 2050: Prospective (Transport sector) 1990 – 2020: Retrospective 2020 – 2050: Prospective
Materials included	Concrete, stone, bricks, gypsum, glass, asphalt, excavated material, metals, wood and wood agglomerate and plastics	Stocks: wood-based material, ceramics and bricks, mineral-binding materials, stone and aggregates, iron and steel and asphalt Flows: Wood, Concrete, Metals and Bricks	Excavation sand, concrete, asphalt, gravel, wood, brick,steel, plastics, flat glass, copper, aluminium	Aluminum, asphalt & bitumen, brickwork, concrete, copper, glass, gravel, sand, and natural stone, iron & steel, mineral wool, other metals, plastics, polystyrene, wood, others

Estimation approach	Bottom-up approach with material intensities and building archetypes. Inflows estimated based on construction databases and estimation from the land-use and development plan. A model has been developed for the estimation of the demolition year to estimate the material outflows from buildings. Inflows and outflows also include major and energy refurbishments.	Bottom-up approach with material intensities and building archetypes. Integration of GIS data. Demolition year supposed equal to construction year plus estimated lifetime (102 years for MF, 96 years for SF)	No information as the model is not publicly disclosed.	(Buildings) Bottom-up approach with material intensities and building archetypes. Integration of GIS data. Demolition material outflows are based on statistical data [101]. (Transport) Land-use data, statistical data, and specific data on material intensities is used to determine material stocks [102].

Achetypes categories	Bottom-up methodology with material intensities based on: • 29 categories of buildings (end-use and year of construction) • 6 categories of roads.	Bottom-up methodology with material intensities based on: • 17 categories of buildings (end-use and year of construction) • 4 categories of roads • 6 categories of pipes	No information as the model is not publicly disclosed.	Bottom-up methodology with material intensities based on: • 4 categories of buildings (use types and year of construction) • 19 categories of transport infrastructures.
Main data sources	• GIS databases on buildings and roads • Databases on construction and road refurbishment and other data from documents and surveys • Rennes Métropole land-use and development plan (PLU), housing plan (PLH), climate and energy plan (PCAET) • CitéSource database on material intensities	• Swedish National Land survey • Local studies [26] • Local standards for construction	No information as the model is not publicly disclosed.	• Individual surveys on material intensities • Literature on material intensities • Land-use plans • Satellite images • Statistical data

Secondary material consideration	Calculation of recycling and reuse rates for current, mid-term and long-term scenarios based on techno-economic analysis of local waste recovery supply chains.	-	-	Potentials for circular economy in urban construction is treated in an individual analysis [17]. Recycling rates are based on individual literature and country wide statistics. A close spatial allocation of landfilling and recycling within the boundaries of Vienna was not possible. Generally, high recycling rates were found in Austria, while debris were and bricks from debris were found to have the highest landfilling rates

4.1 Rennes Métropole

Rennes Métropole is the main urban area of the Ille-et-Vilaine department in the region of Brittany in France. The metropolitan area has a population of around 457 000 inhabitants (INSEE). Rennes is a compact city with a well-defined urban core surrounded by suburban areas. The city's built environment is characterized by its mix of historical and modern architecture, including narrower streets in the city center and spacious boulevards in the suburbs. The dynamic and growing population in Rennes Metropole has led to an increased demand for new construction sites and buildings, putting pressure on the city's infrastructure and environment.

The CREATE project partner CitéSource is located in Rennes and the company has already been involved in several studies on the construction sector and circular economy in this area. The recently published study of the urban metabolism of Rennes Métropole provides data and insights on the quantities of stocks and flows in the construction sector of Rennes Métropole [1]. Furthermore, the study provides a projection of construction material inflows and outflows until 2030. CitéSource and its partner Neo-Eco also conducted a techno-economic analysis of local construction waste recovery processes giving an estimation of the available secondary materials in Rennes Metropole [1]. The following chapter gives details on the methodology used to estimate the stocks and flows and to develop future scenarios, the main sources of data used, and the hypotheses considered to evaluate the availability of each construction material. A detailed description of the calculation methodology and hypotheses considered is available in the published report for Rennes Metropole.

4.1.1 Material stocks and flows model

CitéSource estimated the current stock of construction material for the buildings and road infrastructures in Rennes Metropole. Both stock calculations are based on a bottom-up approach, as detailed in . The building categorization used to apply the bottom-up methodology is based on previous work conducted by CitéSource [1] and contains 29 types of buildings ,*e.g.*, residential individual, residential collective, or commercial, and year of construction. The material intensities per square meter for each building type have been estimated depending on the construction methods and materials involved. The total stock per material is calculated as a product of this material intensity and the total gross surface area for each building category. The same bottom-up approach is applied to calculate the material stocks for the road infrastructures. Five types of stocks are defined, with different material intensities depending on the type of pavement used and their hierarchy within the road network, *e.g.*, local roads, and regional roads. The analysis focuses on the following groups of construction material: concrete, stone, bricks, gypsum, glass, asphalt, other non-metallic minerals, excavated material, metals, wood and wood agglomerate and plastics.

The construction material flows calculation performed by CitéSource has been calculated from 2017 to 2030 and is presented in Figure 9. The first two years (2017-2019) are a retrospective of the current inflows and outflows based on available local data. From 2020 to 2030, the projections rely on objectives defined in the local housing plan and energy and climate plan. It includes the material inflows and outflows generated by building construction, demolition, refurbishment (major refurbishment and energy refurbishment), development of local roads, and renewal of the road network. In particular, the amount of material necessary for the building construction is estimated based on the local housing plan (PLH) in Rennes Métropole, providing information on the number of buildings to be built per city and their type. The estimation of the building demolition flows based on the calculation of a demolition coefficient applied to the built surface. The refurbishment flows are estimated based on the number and types of building to be refurbishment according to the local plans. A material intensity is estimated for refurbishments and used to calculate the flows for each type of building, following the bottom-up approach presented.

4.1.2 Waste treatment and secondary material availability

The part of the construction materials outflow that is locally available as secondary material is highly dependent on the characteristics of the local waste recovery processes. CitéSource and its partner Neo-Eco conducted a techno-economic analysis of the material local supply chains for concrete, metals, wood, excavated material, gypsum, glass, plastics, and insulating materials. This analysis led to the development of three scenarios (current, mid-term, and long-term scenarios) characterized by different recycling and reuse rates. These rates enable the estimation of the available construction secondary material per year based on the calculated outflows. For all three scenarios, a margin of 0.5% is considered for potentially polluted outflows.

4.1.3 Data analysis

Excavated materials make up the highest share in occurring construction outflows in the metropolitan area with an average of 507 kt per year over the period 2020-2030. Beside excavated materials, the average annual construction outflows in Rennes Métropole comprise 157 kt of concrete, 83 kt of bituminous mix wastes, and 34 kt of stone. A complete overview on occurring construction material outflows, wastes and recycled/reusable material available for the different periods considered in the CitéSource study can be found in Figure 9.

Material consumption greatly exceeds the occurrence of construction waste in both the metropolitan area and in Rennes city. Concrete makes up the highest share in material consumption with 1413 kt per year in average in the metropolitan area with only 147 kt of recycled/reusable concrete per year in average for the period 2020 - 2030. Figure 9provides a complete overview on the materials consumed by the construction sector in Rennes Métropole for the different periods considered (inflows).

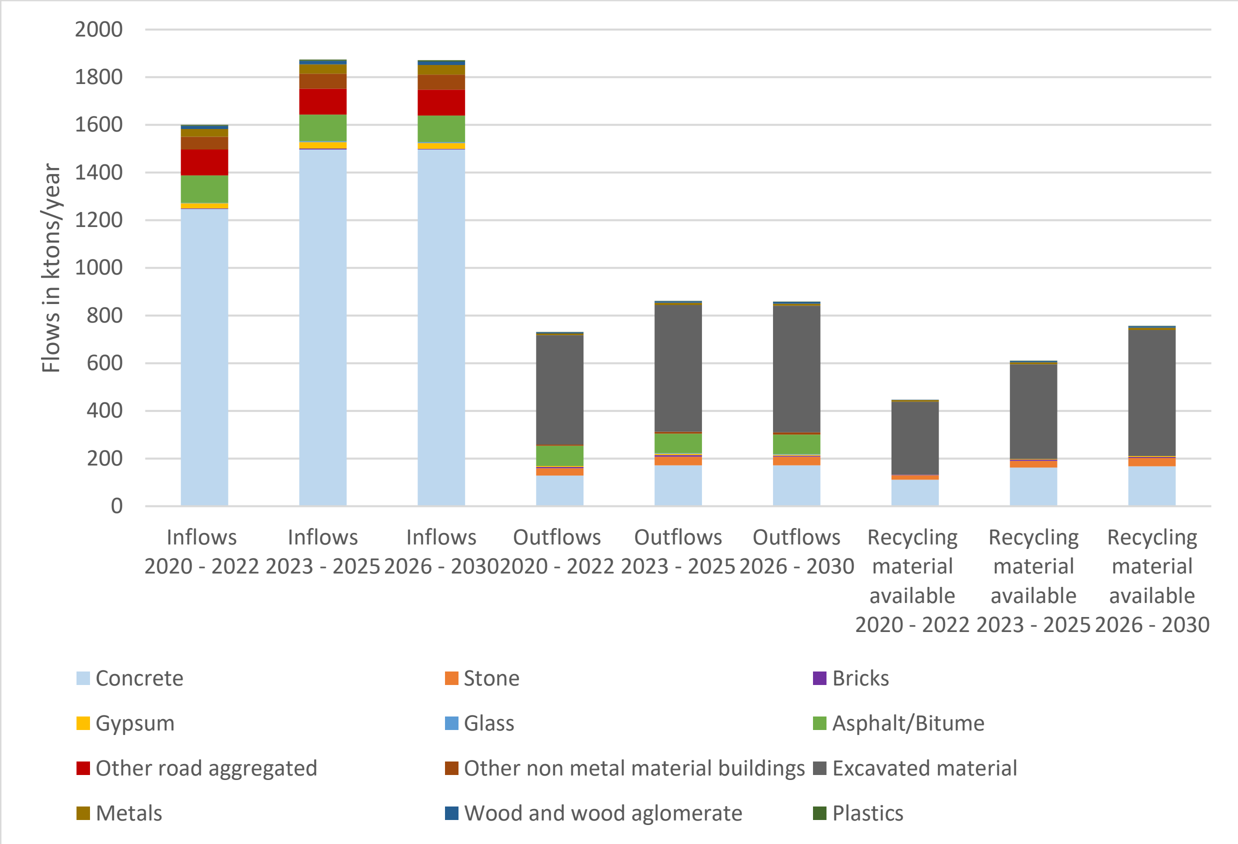

Figure 9: Yearly inflows, outflows and secondary material available per material in Rennes Metropole (CitéSource)

4.2 Gothenburg

Gothenburg is a city located on the west coast of Sweden and is the second largest city in the country with a population of approximately 585,000 inhabitants (SCB). The city is known for its mix of historical and modern architecture, with well-preserved 19th century buildings in the city centre and modern residential and commercial developments in the suburbs. The population of Gothenburg has been growing rapidly in recent years, driven by immigration and economic development. This growth has put pressure on the city's infrastructure and built environment, particularly in terms of housing and transportation.

The CREATE partner Chalmers University of Technology has extensive experience with construction material stocks and flows analysis. A particular focus has been put on developing a reliable and spatialized construction material stock model and a material intensity database for residential buildings has been developed at the country level in Sweden to support bottom-up stocks and flows mapping approaches [26]. A specific construction material stock model, based on refined material intensity and spatial data, has also been conducted for the city of Gothenburg [103].The flows analysis has been performed within the framework of a Master

Thesis, focusing only on residential buildings and four categories of construction materials [50]. The following paragraphs present the details and assumptions of the stocks and flow model developed, the data sources, and the results obtained.

4.2.1 Material stocks and flows model

The analysis of the current urban material stock of the city of Gothenburg has been performed based on the spatial analysis of material stocks and clustering algorithm methodology developed by Gontia et al. [103]. The scope of the analysis of the material stocks entails buildings, roads, and pipes and includes the following material types: wood-based material, ceramics and bricks, mineral-binding materials, stone and aggregates, iron and steel and asphalt. The methodology follows the guidelines of a bottom-up material stocks analysis. Building archetypes were derived based on the type of use, including residential buildings divided into multi-family residential buildings, single-family residential buildings, non-residential buildings (classified based on their function: economic, industrial, and public buildings), and year of construction. Typical architectural plans and specifications were available for each archetype, which allowed for the estimation of material intensities. Material and dimension takeoffs resulted in a detailed understanding of the type and volume of construction material. Densities of construction materials were then used to obtain material masses, which were then divided by the building's floor area to obtain material intensities expressed in kg/m2.GFA (Gross Floor Area). These takeoffs resulted in the volume of each material in the building, to which material densities were applied to obtain the type and mass of materials in each archetype [26]

This bottom-up approach has also been applied to the road network, where roads and bike lanes are differentiated. The roads are further divided depending on the annual daily traffic criterion. Considering pipes both drinking water and waste treatment pipes have been included in the analysis. The material intensities differ depending on the pipe's year of construction and diameter and most data were taken from previous studies and local manufacturers. It is worth noting that pipe stock modeling was restricted to the pipe themselves and thus does not reflect the entirety of materials that were put in place to build the pipe networks, such as drainage aggregates.

Future stocks and inflows and outflows scenarios have been developed in a master thesis aiming to evaluate the potential of reuse and recycling of residential construction material in the city of Gothenburg [50]. The scope of this study included only residential buildings (single and multi-family) and the following four construction materials: wood, bricks, concrete, and metals included in the roof, the bottom slab, the exterior walls, and the windows. Rough estimations on the demolition and construction rates were necessary to estimate the outflows and inflows of construction material within the framework of the master thesis. An average lifetime, assumed to be 102 years for single family buildings and 96 years for multi-family buildings, was added to the construction date to obtain an estimated demolition year. Those assumptions are, however, too rough to fully characterize the demolition outflows due to uncertainties and the absence of probability distribution for the building life times. Based on local project plans and interviews with local stakeholders, future construction hypotheses have been made to account for construction material inflows.

4.2.2 Data analysis

The total construction material stocks in Gothenburg, including buildings, roads, and pipes in 2016 amount to 84 million tons. As highlighted in Figure 10, buildings (including single family, multi-family and non-residential buildings) account for 80% of the total stock. The residential buildings alone account for 56% of the total building stock. Roads represent 19% of the material stock and the remaining 1% of the stock is in pipes. Almost 50% of this stock is mineral bindings material (including concrete), followed by stones and aggregates (20%) and ceramics (10%) as highlighted in Figure 11.

The analysis of the data on flows for residential buildings (MF and SF) enables the calculation of yearly average construction and demolition rates. These values are used to approximate the yearly material inflows and outflows for residential buildings. Figure 12 presents the results for the decade of the year 2010. The main inflow is concrete with a yearly average inflow 6368 ktons. For the same period, the main outflow is wood, with a yearly average outflow of 2082 ktons.

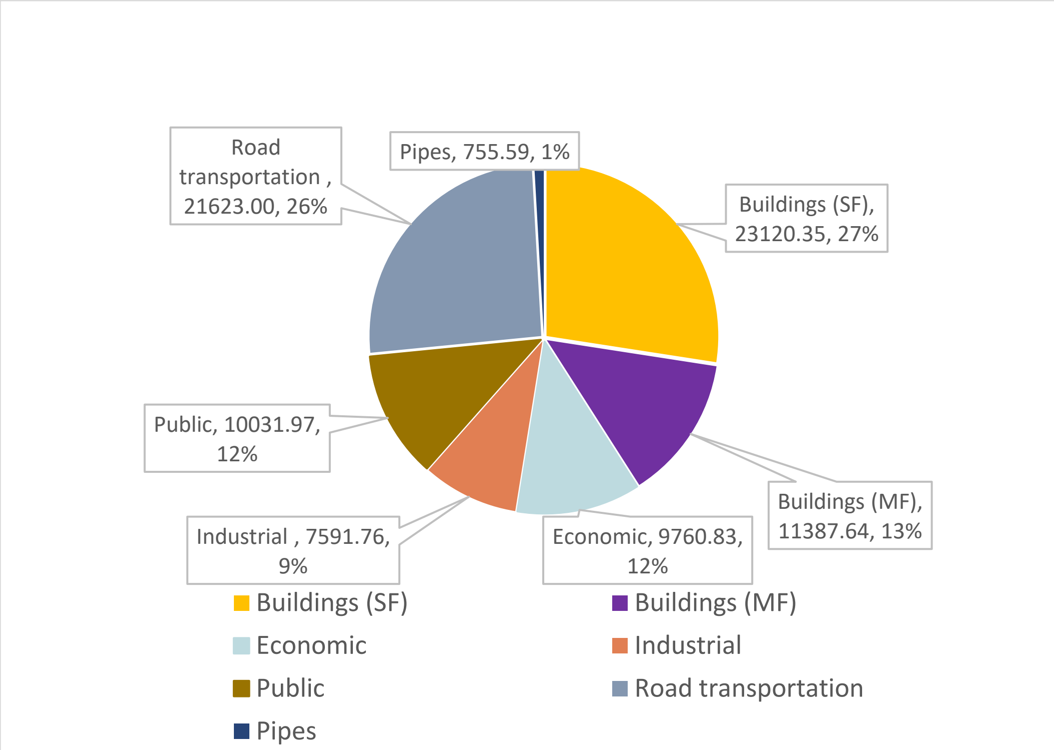

Figure 10: Distribution of construction material stocks per category in Gothenburg in % (2016) (Source: [79])

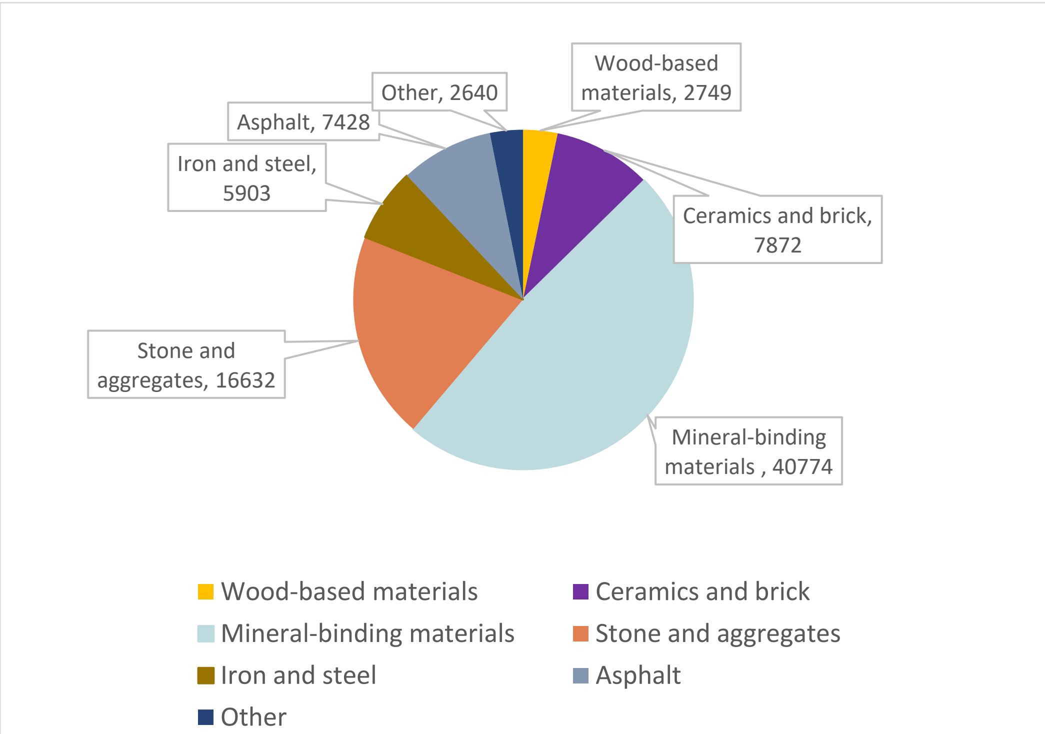

Figure 11: Construction material stocks per material type in Gothenburg in ktons (2016) (Source: [79])

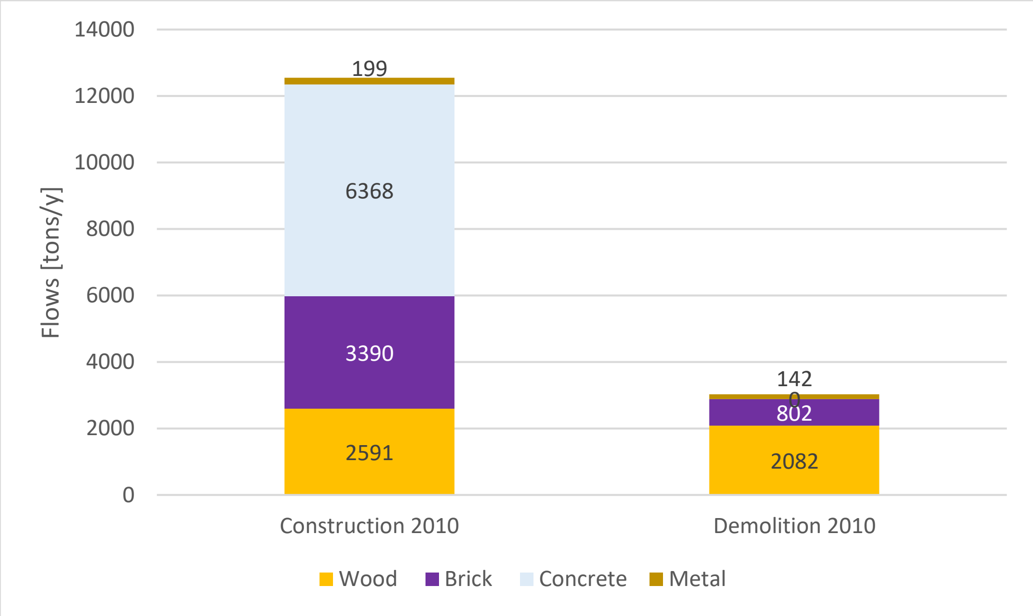

Figure 12: Average annual construction material flows for residential buildings in Gothenburg (2010) (source: [50])

4.3 Njimegen

The city of Nijmegen forms the centre of the urbanized fluvial area in the eastern part of the Netherlands near the German border. It is one of the oldest cities of the country with a history dating back to Roman times. Nijmegen is a growing city with more than 175,000 inhabitants and a population density of 3,000 inhabitants/km2 that has a long track record on sustainability, as it won the European Green Capital award in 2018. Today, the city has a strong circular ambition regarding sustainability and housing development written in its political strategy (`Nijmegen 2040`). Indeed, Nijmegen wants to reach 25% of circular construction by 2025 and 50% by 2030 with the goal to be 100% circular and 0% loss of raw materials by 2050. This ambition is in line with the strategy of the Region Arnhem/Nijmegen.

The consultancy Metabolic published a regional vision and implementation program for a circular Nijmegen [15]. More precisely, the report entails the region “Rijk van Nijmegen”, which also includes the municipalities of Beuningen, Berg en Dal, Heumen, and Wijchen. The report provides a substance flow analysis of the construction sector, which is the basis for the discussion of construction material flows in Nijmegen presented in the following section.

4.3.1 Material flows model

According to Metabolic, the model used in the report is a snapshot from the year of the report (2016) and relies on available open data, and not on field analysis and municipality specific data. The recommendation of Metabolic is to perform a new assessment of the construction material stocks and flows using a model newly developed by Metabolic to obtain reliable data. This model is based on the definition of building archetypes from the Netherlands and was developed in cooperation with partners from the construction industry. The model considers 20 different material types and could provide information on material stocks and related embodied environmental implications by linking material masses to the Dutch Environmental Database (NMD) [104] that provides LCA data specific to the Dutch context. Required inputs include geospatial data on building types and build periods. Furthermore, the consideration of issued building and demolition permits of upcoming years can be linked to this model to provide insights into possible scenarios on future material flows. Based on a conducted interview with Metabolic, it was recommended to update the existing model for Nijmegen with the above outlined methodology [2].

4.3.2 Data analysis

Construction material inflows are dominated by excavation sand (3,238 kt), concrete (523 kt) and asphalt (152 kt). Figure 13 provides an overview on the construction material inflows in Nijmegen.

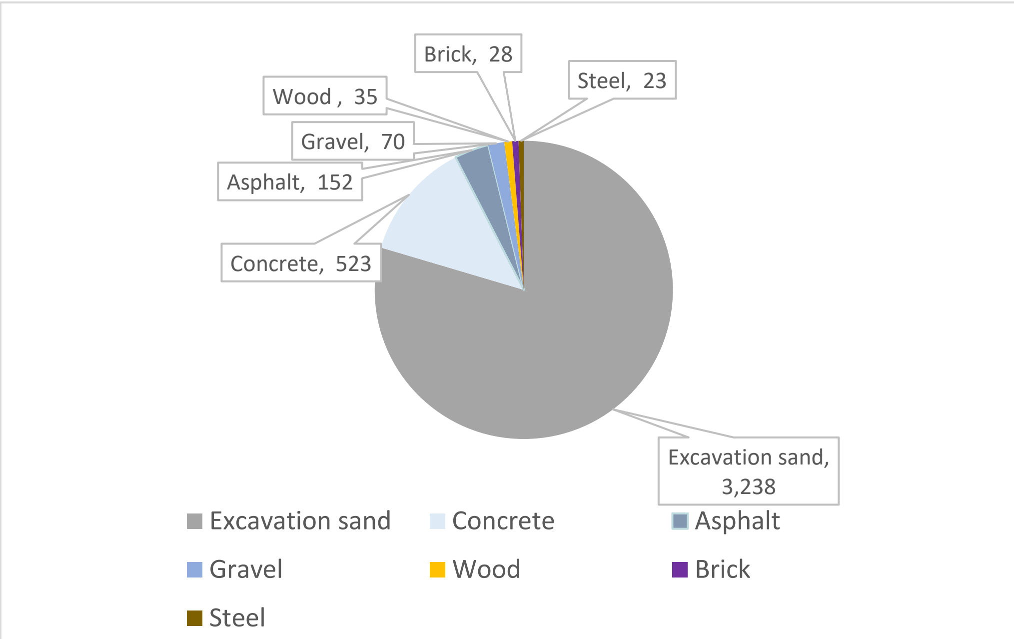

Figure** 13 **Construction material inflows Nijmegen in kt/y (2016) (source: [19])

Like in Rennes and Gothenburg, construction waste outflows are with 359 kt/a much lower than construction material inflows in Nijmegen (4,078 kt/a). Figure 14provides an overview on the construction material outflows in Nijmegen. Rubble and asphalt comprise the main construction material outflows in Nijmegen.

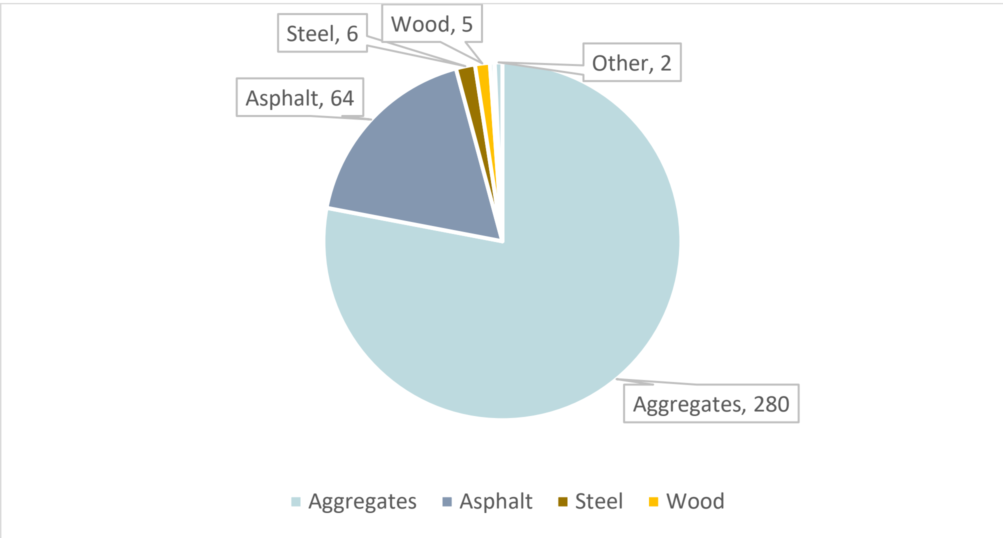

Figure 14 Construction material outflows Nijmegen in kt/y (2016) (source: [19])

4.4 Vienna

Vienna is the capital of Austria, located in the eastern part of the country. It is one of the largest cities in Europe, with a population of approximately 1.9 million people and is home to a rich cultural heritage and history, with a well-preserved historic center that is a UNESCO World Heritage site [105]. The city has been growing over the past few decades and this growth has put pressure on the city's infrastructure and built environment particularly in terms of housing, transportation, and environmental sustainability.

Vienna has served as case study for several highly ranked scientific publications in the field of circular economy in urban construction. For instance, Kleemann et al. introduced a change detection based methodology to assess urban demolition waste occurrence and compositions in Vienna [106]. In subsequent works, Lederer et al. provide in depth analyses of construction material flows [7] and circular economy potentials for the construction sector of Vienna [101]. Hence, the following paragraphs are mainly based on the data provided in the papers published by the active group of researchers around Jakob Lederer from TU Wien.

4.4.1 Material stocks and flows model

The papers analysed originate from the research group around Jakob from TU Wien. Their stock and flow analyses are differentiated in the building sector and the transport sector. Hence, the following section follows this differentiation and details on the available models and results.

4.4.1.1 Building sector

The available building stock material model for Vienna relies on a set of building categories from different building periods that is linked to a dataset of specific material intensities for each building group [107], and a GIS dataset that contains the gross volume, building category, and building period for each building in Vienna [3,4]. The specific material intensities were initially based on a subset of 66 buildings that were analysed according to site visits, construction plans, and available literature [3]. In a subsequent study, the applicability of more detailed reference values to map material intensities was investigated, widening the sample size to 256 buildings [107]. The material intensities of those buildings were examined based on construction plans. Compared to the previous study [3], a difference of 1 - 25% was found across the material intensities, where insulation materials were particularly underestimated [107].

Retrospective material flows for the building sector were determined based on retrospective construction and demolition activities. Projections for construction material flows were provided on the bases of a business as usual scenario, a high demolition rate scenario, and a high renovation rate scenario [7]. A related study combines construction material stocks and flows from the building and transport sector to provide an assessment of the potentials for a circular economy of mineral construction materials and demolition waste in Vienna [17]. The potential assessment combines material flow assessments with landfilling rates, recycling rates, and substitution potentials for primary materials to derive a circular construction scenario. As the materials from this paper include the building sector and transportation infrastructure sector, these materials are taken as basis for the material stock and flow data discussed in section 4.4.2.

Figure 15shows the building sector material stock development from 1990 to 2015 as well as for the above-mentioned scenarios. The increase in concrete material stock between 2015 and 2050 can be highlighted, as the underlying study assumes a continuation of current construction practices [7].

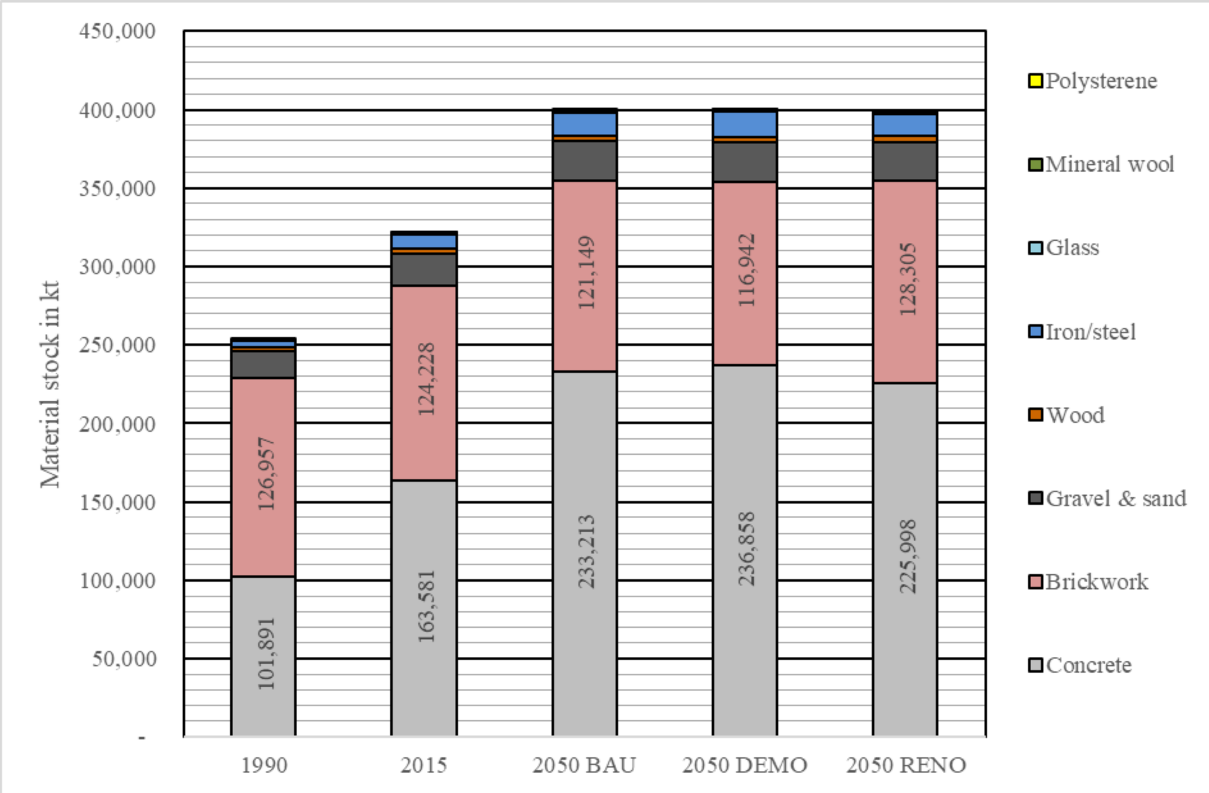

Figure 15 Construction material stock for the building sector in scenarios developed in [7]

Figure 16indicates the expected material inflows and outflows form the building sector in Vienna for the above-mentioned scenarios. As demonstrated in [17] and discussed in chapter 4.4.2, many of the material outflows can be reused in recycling construction materials.

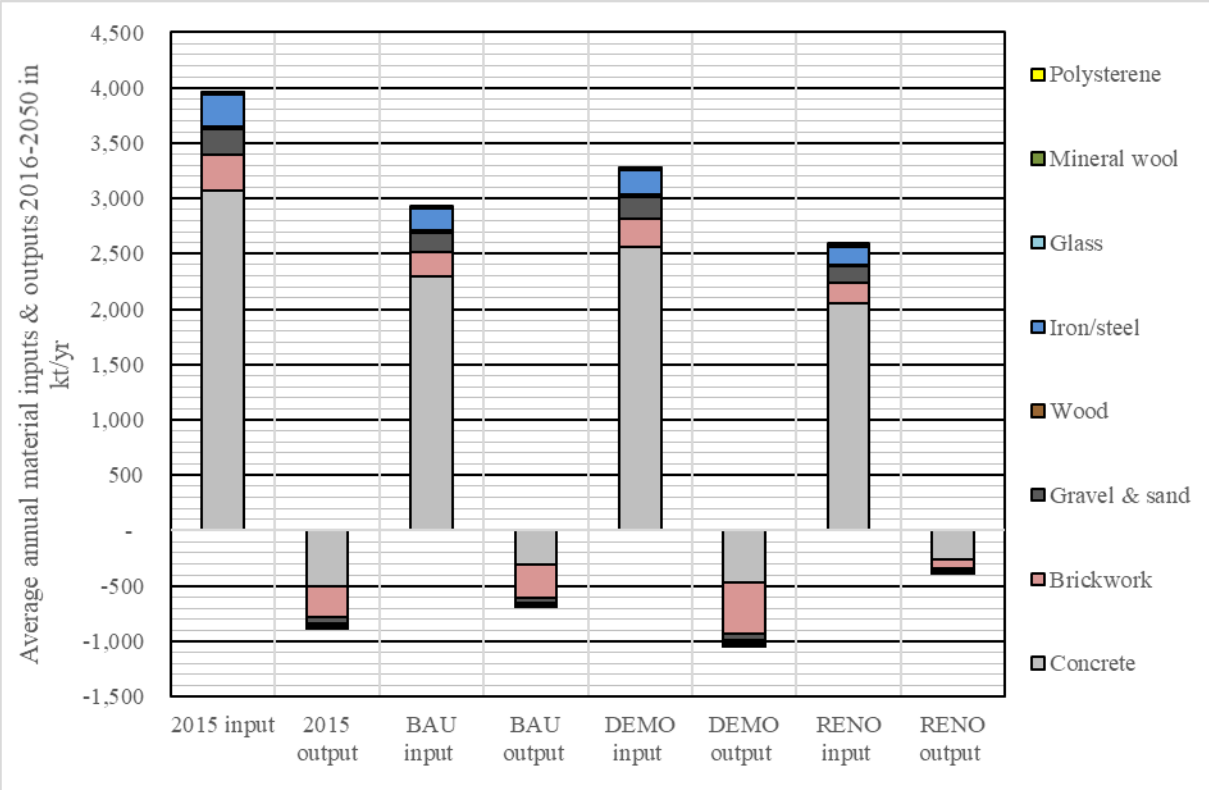

Figure 16 Annual material inputs and outputs for the building sector in scenarios developed in [7]

4.4.1.2 Transport sector

Beside the building sector, the group of Lederer et al. also put a focus on material stocks and flows in the transport sector. The transport sector is divided into vehicles and infrastructures, and further distinguishes between motorized, non-motorized individual transport, and public transport. Additionally, roads and rail infrastructure are differentiated. The methodology to derive material stocks and flows involved the definition of “service units”, *e.g.*, m^2 of road, or length of metro lines for the different transport modes. Combined with material intensities from literature and statistics about renewal rates and maintenance activities, the statistical data on service units allowed the derivation of material stocks and flows for infrastructure in the transport sector of Vienna [102]. To ensure a consistent scope of materials, vehicles are excluded for the considerations made in CREATE.

The retrospective analysis of material stocks and flows in transport infrastructure reveals that material stocks are dominated by road and rail infrastructure, whereas public transport and non-motorized individual transport material stocks have been increasing. Furthermore, the aspect of maintenance is highlighted in material consumption, as the transport system in Vienna is already well developed [102].

Regarding the projection of construction material flows, Gassner et al. consider three different development scenarios in addition to business-as-usual:

- A_{BAU}: A business-as-usual scenario that extrapolates current practices and developments
- B_{+BEV}: A battery electric vehicle fleet scenario that assumes the replacement of fossil driven cars by electric vehicles and otherwise mostly unchanged modal split
- C_{+PT}: A public transport focused scenario where motorized individual transport is largely replaced by public transport
- D_{+AM}: An active mobility focused scenario that assumes a strong increase in non-motorized individual transport and moderate increase in public transport use

Figure 17indicates the material stock development in the scenarios described above. It shows the effects of shifts in transport modes on the required infrastructure and subsequent material usage and requirements.

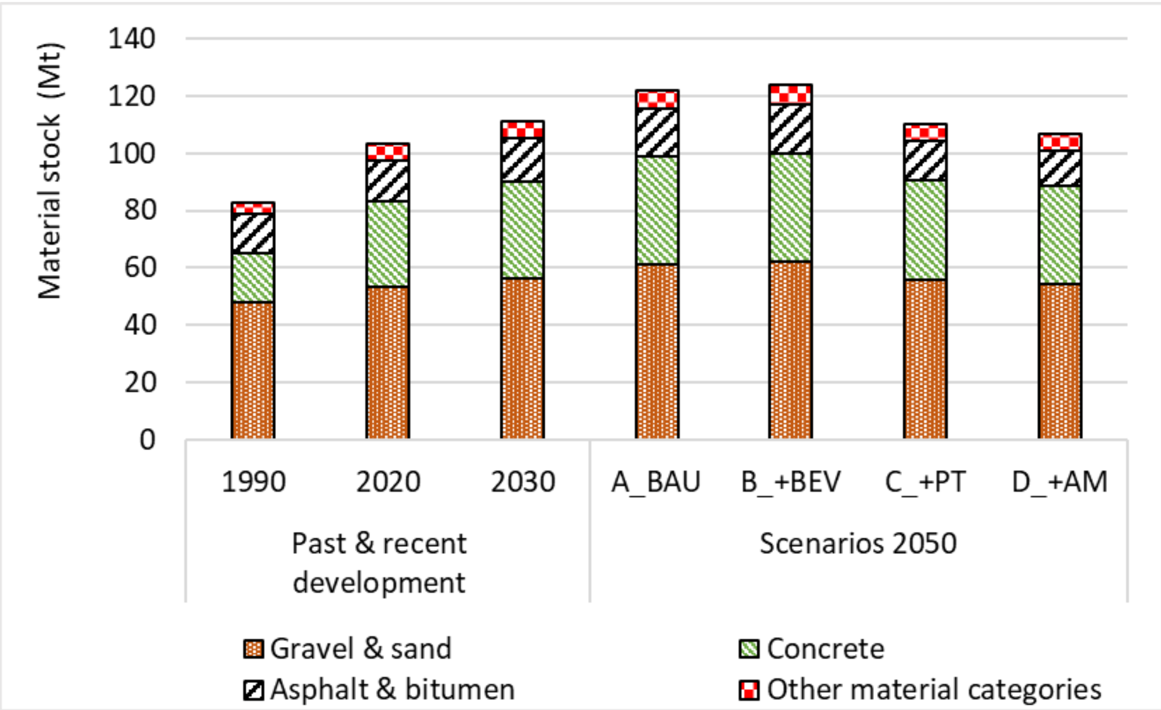

Figure 17 Material stock development in transport sector for the scenarios determined by [52]

4.4.2 Data analysis

The following section details on the material stocks and flows for urban construction extracted from available literature. Available findings are related to the CREATE project to be used in the development of sustainable construction scenarios. As Lederer et al. provide an overarching analysis of construction waste and material flows that also encompasses their findings related to transport infrastructure [17], the results from this paper are used for the considerations on

CREATE. Figure 18shows the current state of construction material inputs for Vienna in the building sector and transport sector. The dominance of concrete use can be highlighted, as well as the high share of gravel and sand and asphalt use within the transport sector.

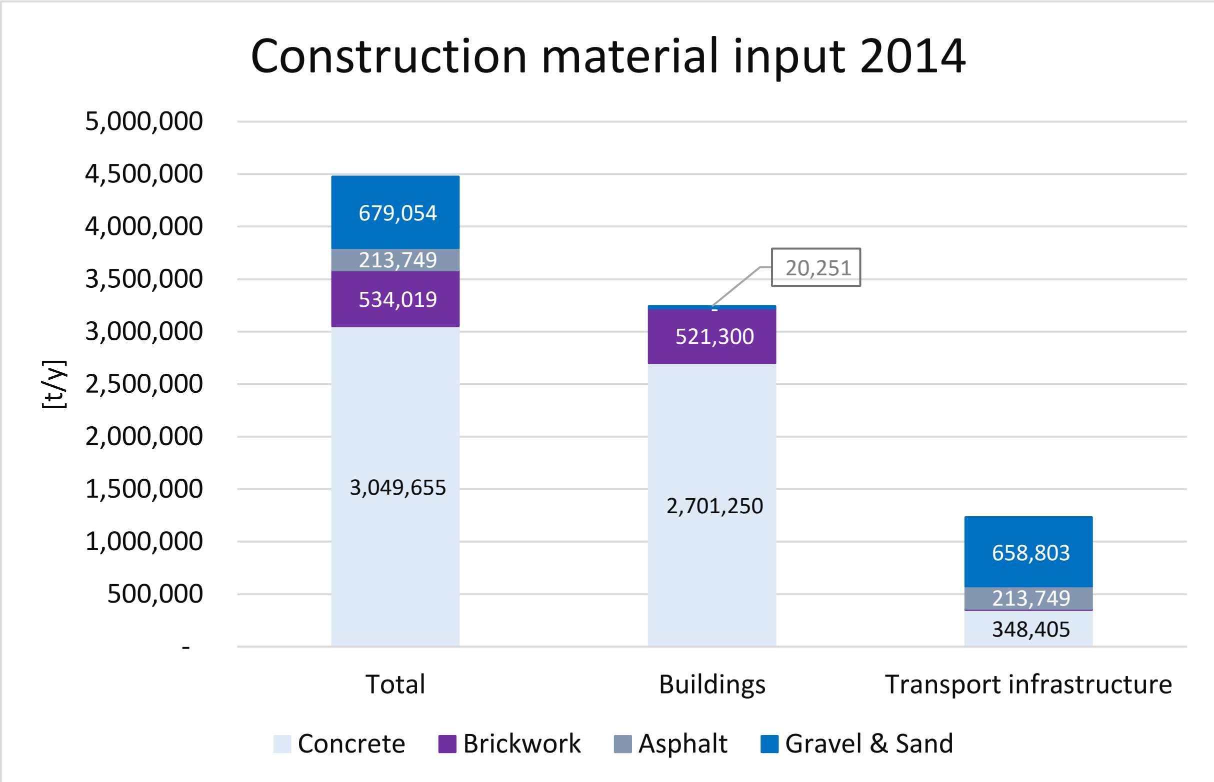

Figure 18 Construction material inputs for the building and transport sector in Vienna 2014 [17]

Figure 19relates construction material inputs to waste flows and shows the *circularity scenario* introduced by Lederer et al. [17]. It shows the effects of demolition waste reuse on the imports of primary and secondary raw materials and on exports of construction and demolition waste. Waste exports of concrete, gravel, and asphalt could be largely reduced, while the complete reuse of debris originating from brickwork is not feasible due to restrictions originating from recycling material standards and quality issues [17,108]. The analysis indicates the potential of circular economy to reduce waste exports and landfilling. Furthermore, Lederer et al. show that a reduction of 32% in primary material consumption would be feasible. However, continuing net material stock additions entail that also a circular use of construction materials could not sustain the current construction material demand [7,17].

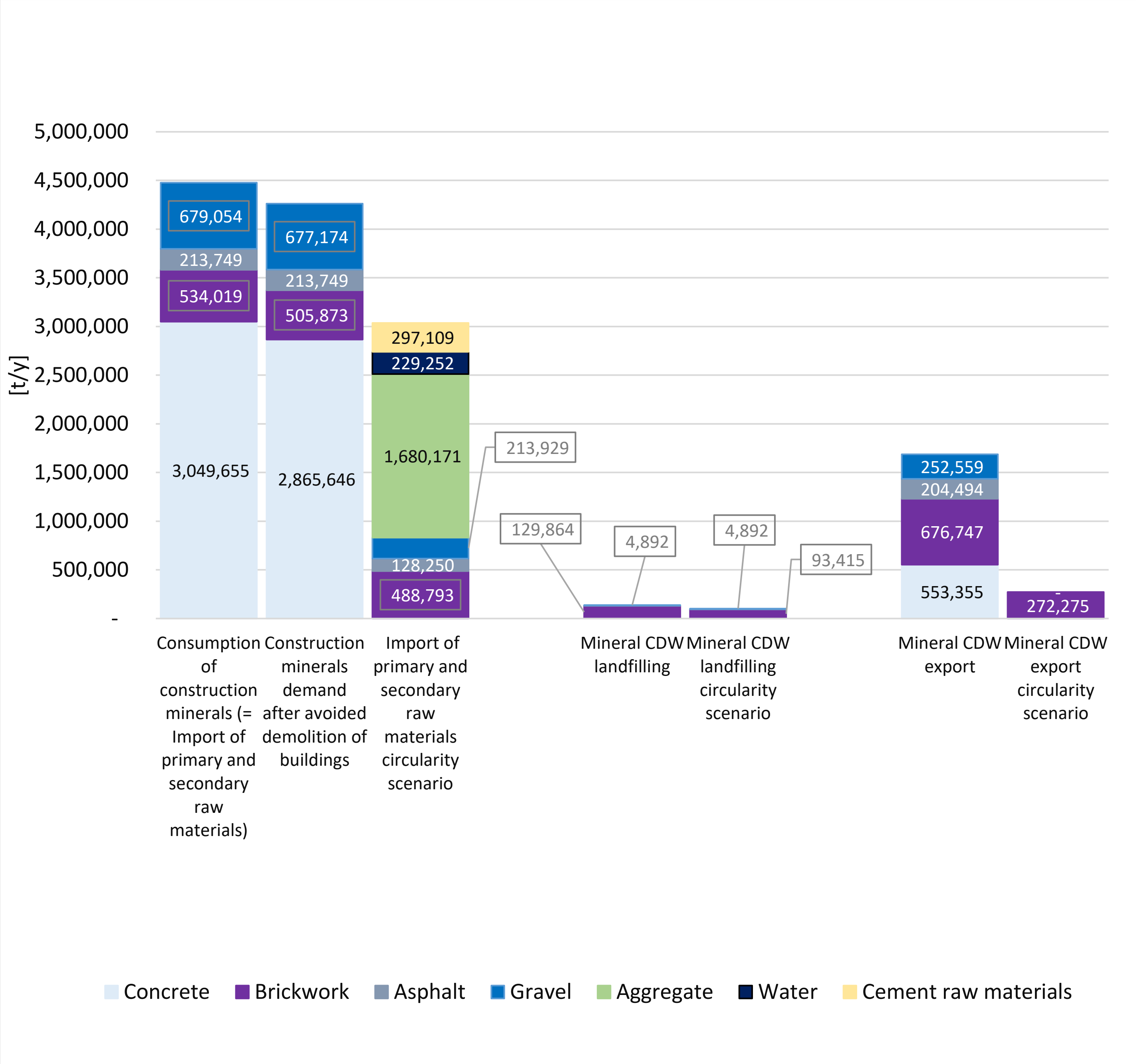

Figure 19 Construction material input and waste flow scenario comparison for Vienna [17]

4.5 Stocks and flows data comparison for the 4 cities

The three ULLs Gothenburg, Nijmegen, Rennes Métropole and Vienna, have a different cultural heritage that reflects in the prevalent and preceded construction styles. Also, different local groups of researchers and research questions have led to differences in the availability and quality of stock and flow data. The following section discusses these differences to provide a conclusive picture of material stocks and flows in the construction sector of the ULLs in CREATE.

4.5.1 Data sources

The data on material stocks and flows were acquired within different contexts and with different objectives for each city. Furthermore, the involved research groups applied different methodologies in the assessment of material stocks and flows due to different framework conditions on data availability and quality. This results in varying situations regarding material stock and flow data across the ULLs in CREATE. While in Vienna and Gothenburg the establishment of material stock and flow data was driven by academic efforts, private engineering and research companies carried out the analyses in Rennes Métropole and Nijmegen. This is reflected in the fact the group of Lederer et al. in Vienna developed for example new technologies working with bottom-up approaches [106] and focused on the generalizability of results for the whole city [7]. The analysis conducted for Rennes Métropole aims to be a direct decision making basis for the implementation of a circular economy strategy [1]. Hence, it contains a more detailed reflection of the local construction industry and already identifies some of the key development areas for the implementation of such a strategy. Additionally, the mapping of key stakeholders and areas also entailed a spatial localization, which will be useful in the impact assessment of circular construction scenarios [1]. While the available studies in Gothenburg also yield spatial information on materials stocks, no in-depth mapping of priority areas and key stakeholders of the construction industry was carried out [16]. The developed building stock model, however, entails information about construction components, *e.g.*, slabs, walls, and windows, which could become the basis for a component-based assessment of reuse strategies [16].

The review of used data sources in stock and flow modelling in the CREATE ULLs has revealed a focus on modelling based on building archetypes that comprise use types, build periods and building volume. These archetypes are often linked to specific material intensities to obtain construction material stock and flow data. To better reflect the current conditions and projected developments on material flows, it is suggested to further integrate issued building and demolition permits as well as land use plans and potentially building schemes into stock and flow modelling. Furthermore, to better reflect component-level information, the models could be extended by integrating data from demolition audits into the archetypes to potentially derive component reuse potentials. Data sources that can lead to the assessments of reuse potentials for, *e.g.*, concrete are outlined in [109], where construction plans of mass housing sites were used to derive reusable concrete structures.

4.5.2 Material stocks

The construction material stock models in the different cities included in the framework of CREATE do not focus on the same construction materials, which makes the values challenging to compare. Additionally, the available studies for Nijmegen only cover material flows. The ULL is therefore not represented in this subchapter. Despite the differences in used data sources and applied methodologies, there are some overlaps in the main groups of construction materials across the ULLs. To enable a comparison of the ULLs, six categories have been defined. The mapping of the different naming for the main construction materials has been performed based on the data on stocks for each city and is presented in Table 4.

Table 4:Mapping of the different material types included in the stocks and flows models of the cities

Categories	Gothenburg	Rennes Métropole	Vienna
Wood/Wood based material	Wood-based materials	Wood and wood agglomerates	Wood
Bricks	Ceramics and brick	Bricks	Brickwork
Concrete	Mineral-binding materials + stone and aggregates	Concrete	Concrete
Metals	Iron and steel	Metals	Iron & steel
Asphalt	Asphalt	Asphalt/Bitume	Asphalt & bitumen

Figure 20 shows the yearly additional material stocks for wood, bricks, concrete, stone, metals, and asphalt in the three cities compared. The scope includes buildings and infrastructures, as detailed in the previous part. For Gothenburg, the stocks also include pipes for drinking and wastewater, however, the contribution to the total additional yearly stocks is around 1% and is neglected in the comparison.

Considering the absolute numbers, Vienna has the highest yearly additional material stocks for the material included in the comparison (4262 kt/y for Vienna, 1857kt/y for Gothenburg and 1150kt/y for Rennes Métropole). However, Gothenburg has a higher yearly material stock addition per capita, reaching 3.16tons/y/capita. Vienna and Rennes Métropole have similar yearly additional material stocks per capita, with 2.22 tons/y/capita and 2.51 tons/y/capita. In terms of materials, concrete is clearly the biggest addition to material stocks in the three cities.

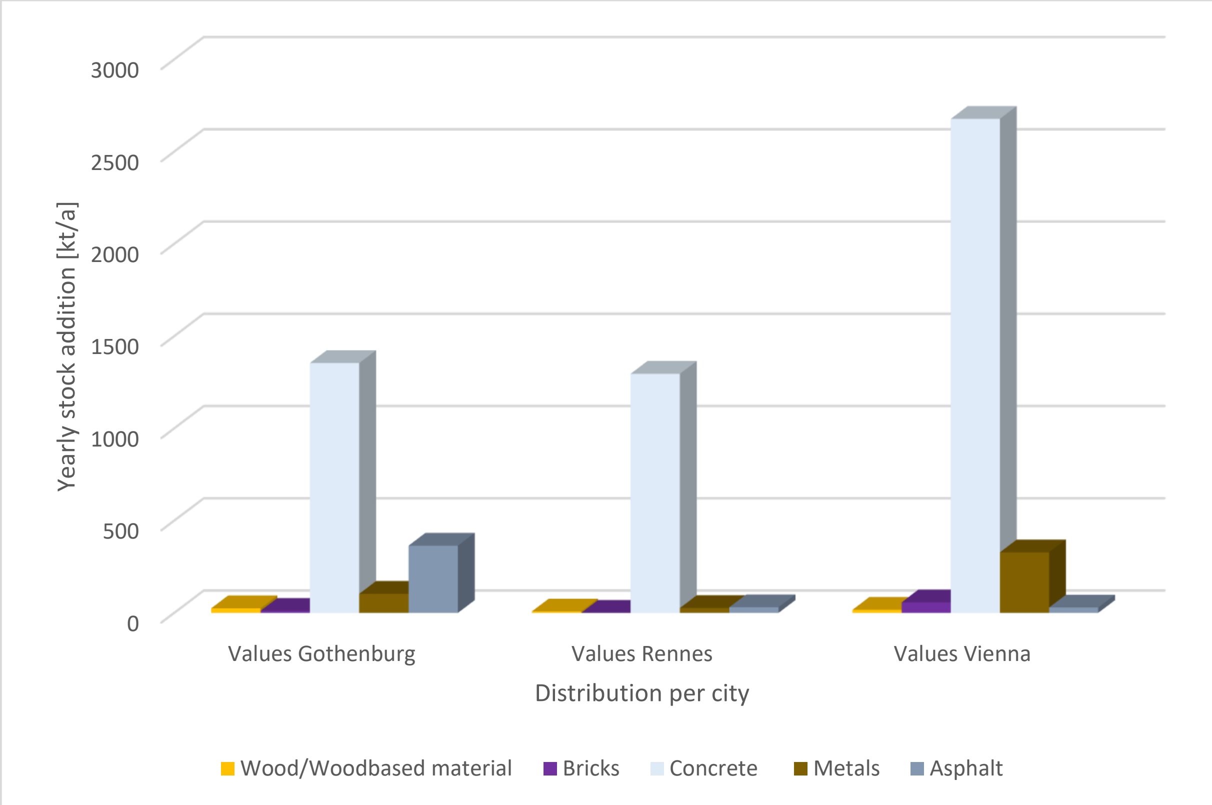

Figure 20: Additional yearly materials stocks in Gothenburg, Rennes Metropole and Vienna

4.5.3 Material flows

The same methodology as for the comparison of material stocks is for the inflows and outflows of construction materials comparison. In this part, only the cities of Rennes Métropole and Vienna are compared due to the scope and restrictions of the flow model developed in Gothenburg that only focuses on certain parts of the buildings, and certain types of materials.

The material inflows and outflows for both cities are compared in Figure 21. Vienna has a higher absolute material consumption and outflows generation. However, as stated before, both cities are comparable in terms of annual material consumption per capita: 3.08 tons/yr. capita in Rennes Métropole and 3.45 tons/yr. capita in Vienna. The material distribution is also comparable in both cities, with concrete being by far the most consumed material, followed by asphalt. Concrete is also the main outflow in each city, followed by asphalt in Rennes Métropole and stones and gravel in Vienna.

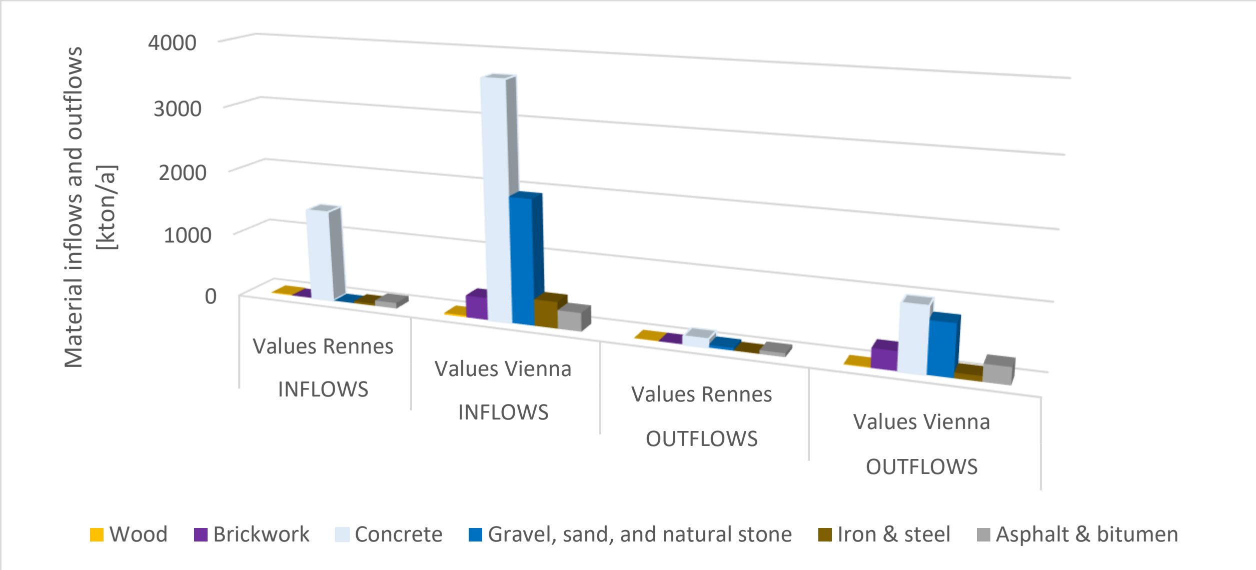

Figure 21: Yearly material inflows and outflows in Vienna (2015) and Rennes Métropole (2017-2019)

Beside the dominance of concrete in material inflows, the comparison also shows a clear general discrepancy between inflows and outflows in both cities, indicating that circular economy principles will only be able to cover parts of the required material input. This finding is important in attempts to generalize the findings developed for the urban development areas considered in CREATE. The general availability of secondary materials will influence the applicability of circular economy principles on the city scale and will be considered in the formulation of policy recommendations developed in WP4. The indicated discrepancy between inflows and outflows, however, also needs to be considered with respect to the substitutability of primary materials by secondary materials. In the case of concrete for example, the currently applied Austrian standard ÖNORM EN 206 [110] defines clear thresholds for recycling aggregate contents in concrete of different compressive strength classes. Lederer et al. demonstrate how these requirements can be considered in the assessment for the potential of secondary construction material reuse and recycling [101]. The same goes for the applicability of concrete reuse. As demonstrated in [111], concrete slabs can be cut and reused in new constructions. This, however, requires more information on the available secondary materials than bare amounts of mass. To provide better estimates on the applicability of secondary material reuse and recycling, material stock and flow models would therefore need to reach beyond the representation of material groups in tonnes of inflows and outflows per year and integrate more qualitative requirements and detailed information about these material groups.

4.5.4 Urban development areas

The assessment of circular economy strategies in CREATE will be carried out based on specific case study areas in each city, the so-called living-labs. As these living labs will comprise the in-depth LCA of certain circular economy strategies, detailed description will be provided in Deliverable 5.2 *Techno-economic model of material and energy supply chains for selected urban cases*. The following section provides a brief introduction to each living-lab site, as specified by the cities and WP4.

Gothenburg ULL:

The living-lab in Gothenburg is comprised of the building stock and construction projects of the public housing company Framtiden owned by the city of Gothenburg. The main question to CREATE considers a detailed mapping of the building stock owned by Framtiden and an assessment of construction materials and components that might become available due to demolition activities. This mapping will be matched with a requirements analysis derived by already planned development areas to provide an indication of possible primary material consumption reductions achieved by material and component reuse. Additionally, the development and validation of new governance arrangements that enhance new business models for all stakeholders engaged is planned. This should promote investments aimed at the application of circular and biobased materials in buildings [112].

Nijmegen ULL:

The living-lab area in Nijmegen will be a construction project that is part of 28 Projects that surround the train station. The sub-project comprises the Hezelpoort complex and includes a tower that will host 383 apartments plus parking spaces and will follow a certain ambition for circularity, depicted in Figure 22. The owner is a social housing company (70% of the flats should be social housing), so economic considerations will be central. Regarding ambitions for circularity and reduced environmental impacts, the tender process included several environmental aspects and KPIs including the MPG Score, adaptivity of the building, construction methods, use of circular materials, and use of biobased materials. The desired MPG score is 0.45m2/year, which is well below the threshold required by law. The MPG aims to integrate life-cycle environmental impacts induced by material use into one key figure and express them using a shadow cost indicator. Furthermore, the project aims to integrate the materials and components used within the Madaster database to facilitate future reuse [98].

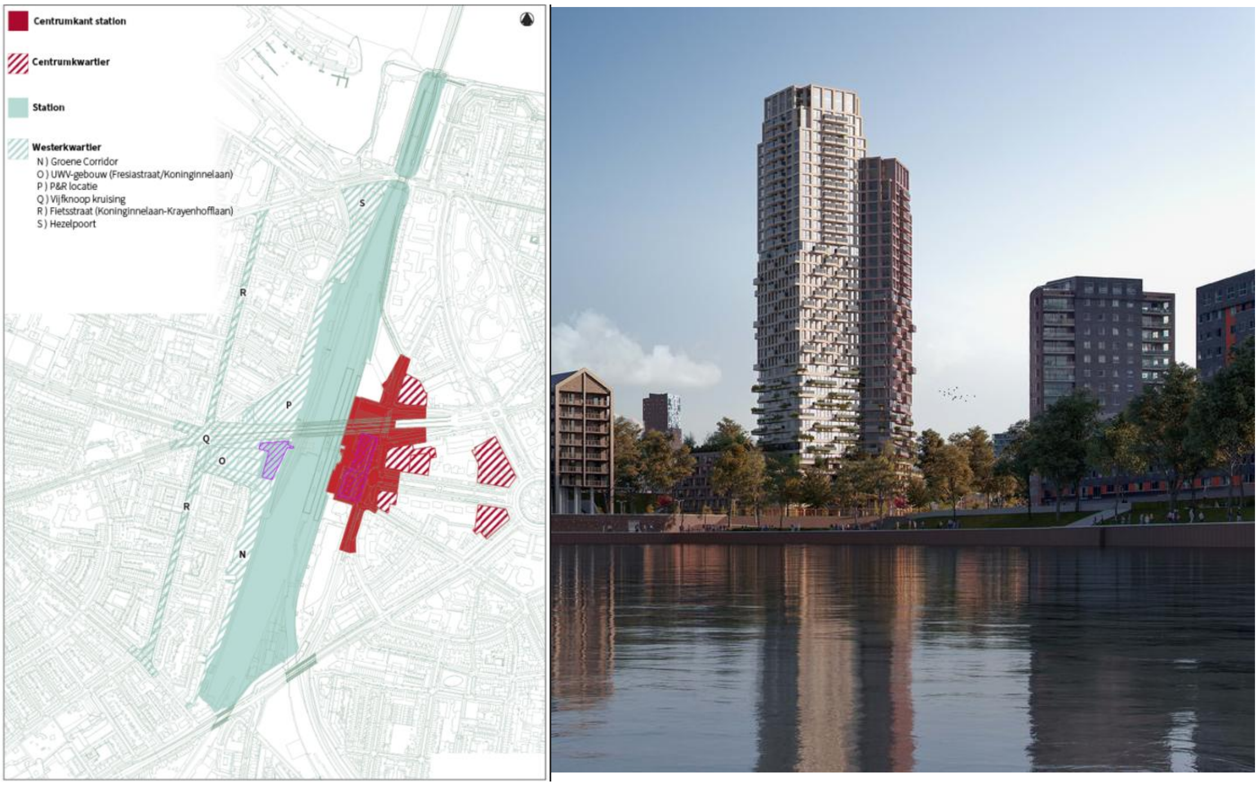

Figure 22 Hezelpoort living lab

Rennes ULL:

Rennes Métropole will comprise two living-lab areas. The first one is the development area "La Bégassière" (Figure 23), which is located Montgermont, 3 km north of Rennes between the main commercial road commonly called the Route du Meuble ("Furniture Street") and the center of the town of Montgermont. It comprises a redevelopment area of 83,000 m². Construction activities will entail the demolition of all currently existing buildings in the area and a redevelopment of a mixed city district [113].

Figure 23: Redevelopment area la Bégassière [113]

The second living lab area will be the "EuroRennes – Technicentre" project. It revolves around the main train station of Rennes, which is owned by SNCF. Beside demolition activities that will allow new rail developments, the repurposing of the existing train maintenance halls is planned. The ambition of the project in this sector is to reconvert the site into a city district with a cultural vocation [113].

Vienna ULL

In Vienna there will be a new development area in Rothneusiedl. The case study area has already been subject to the national research project KLIMUR [114], where potentials for innovative urban farming and climate resilient urban development were assessed. The study area comprises 124 hectares of development are that should provide residential buildings, office buildings and service buildings [115]. Table 5 provides an overview of the expected gross floor areas per usage category.

Table 5 Expected gross floor areas per usage category in Rothneusiedl [115]

Usage category	Expected gross floor area [m²]
Residential	900,000
Office	100,000

Service and industry	238,000
Central functions	150,000
Social infrastructure	75,000
Mobility hub	96,000

The development concept for the area is not yet finalized, however, the KLIMUR project developed several possible configurations of urban planning layouts that accommodate the desired gross floor areas. Figure 24 shows the baseline configuration for the building layout that will be considered in the CREATE project.

Figure 24 Baseline concept for urban planning in Rothneusiedl. Color legend: turquoise: residential, pink: central functions, orange: social infrastructure, blue: mobility hub, dark grey: office, grey: service and industry

The ULL Vienna will benefit from the available studies conducted by the research group around Jakob Lederer, and the results of KLIMUR. The city will be provided with indications on potential secondary material use and related environmental implications in Rothneusiedl.

5 CONCLUSION

In recent years there has been a growing interest in the circular economy of construction materials, which involves the reuse, recycling, and recovery of materials at the end of their life-cycles. Stock and flow modelling of construction materials has consequently become an important tool for evaluating the available resources at the city level. The current state of construction materials stocks and flows in the CREATE ULLs has been reviewed to provide an overview of available secondary materials and methodologies applied for their assessment at urban scale. The review has highlighted the need to consider the constraints related to the assessment of secondary material flows to be used in recycling or reuse activities.

Construction material stocks and flow modelling is a complex task that requires careful consideration of the different scopes that are involved (spatial, temporal, and technical). The technical scope refers to the level of detail that is considered, *i.e.*, distinction between materials and components and technical specifications of materials and components. Currently, stock and flow models for the CREATE ULLs focus on assessments on the material level without detailing on the technical specifications of those materials. The availability of data on stocks and flows of construction components can be classified as low, which stands in contrast to the attributed potentials in environmental impact mitigation related to component reuse that is stated in the waste hierarchy [22]. Relevant modelling approaches at the urban level include material flow analysis (MFA), energy flow analysis, and extended waste MFA (EW-MFA), each of which has its own advantages and drawbacks when applied at the urban scale. MFA is useful for analysing the flow of materials within a specific region, while energy flow analysis is useful for analysing the energy requirements and greenhouse gas emissions associated with the use of construction materials.The adapted version of the EW-MFA methodology developed within the CityLoop project is particularly useful in the context of circular economy strategies, as it enables the quantification of the flows of waste and recycled materials. However, these modelling approaches are often data-intensive and require detailed information on the various sources and sinks of materials.

Assessing the flows of secondary materials for the implementation of circular economy strategies involves analysing not only the presence of resources but also the recovery potential and utilization potential of these resources. This requires consideration of the geographical and temporal availability of secondary materials, the technical and legal constraints in terms of processing and use of secondary materials, the economic viability, and the local legal, social and governance contexts. For example, the availability of certain materials may be limited or their recovery may be hampered by technical or economic constraints. In many cases, urban level information on materials and components including their technical condition is not available, which therefore limits the possibilities to formulate reliable ambitious circular economy strategies at urban scales. To fully understand the related potentials, it is therefore recommended to broaden the scope of existing stock and flow models to integrate information on the component level and provide better information on the expectable technical condition materials and components related stocks and outflows.

To provide a comprehensive understanding of the environmental impacts related to circular economy strategies for construction materials and components over their entire life-cycle, it is important to combine material flow analysis with LCA. This approach enables a multicriteria analysis that assesses the environmental impact of circular economy strategies compared to the use of virgin materials, ranging from the impact of primary material extraction, production, use, and end-of-life management. While the application of LCA approaches can be challenging due to the required data and necessity to closely reflect the local contexts of supply chains, LCA can be an important tool to assess the potential benefits of circular economy practices in urban construction. Reliable information on related environmental impacts is fundamental in the identification of suitable sustainable practices in the transition towards a more circular construction sector.

The second part of this deliverable involves comparing the modelling approaches used in currently available studies on the ULLs Rennes Métropole, Gothenburg, Nijmegen, and Vienna to evaluate the stocks and flows of construction materials. The models used in these cities share similarities in terms of the methodologies used to assess the existing building and infrastructure stocks and flows. The methodologies applied in Vienna, Gothenburg, and Rennes employ a bottom-up approach that relies on the use of building archetypes that are based on literature review and field analyses. These archetypes differentiate building use types and build periods and are linked to statistical data on construction activities and building registries. Material intensities related to the established archetypes then allow a spatial representation of construction material stocks in the ULLs. Notable differences in these approaches across the ULLs involve studies for Vienna detailing material stocks in the transport sector [102], and assessing the potentials for a circular economy of mineral construction materials and demolition waste [101]. The model developed for Gothenburg integrates material intensities on the component level, with detailing on component reusability [16], and detailed assessments specific to the considered case study area are available in Rennes. There are also differences in the hypotheses used in the different models to estimate the construction and demolition rate and to derive information on inflows and outflows. The differences in the scopes and the materials focus make it challenging to compare the results between the different cities. Nevertheless, concrete appears to be the main material in material stocks and flows for the studied cities and can be attributed to high recycling and reuse potentials. While being recycled mostly in road infrastructure in Vienna [101], waste concrete can be recycled and, given the proper dimensions and technical properties, even be reused [111]. The following deliverables 5.2 and 5.3. will explore the recycling and reuse potentials related to the stock and flow models screened for the ULLs and their environmental implications, employing LCA methodologies that reflect the local contexts.

6 REFERENCES

[1] CitéSource, Neo-eco. Etude de métabolisme territorial à l ’ échelle du territoire de Rennes Métropole. 2022.

[2] Roemers G, Reynaud C, Horak D. Meeting Minutes: Exchange on available stock and flow data in Nijmegen for CREATE. 2022.

[3] Kleemann F, Lederer J, Rechberger H, Fellner J. GIS-based Analysis of Vienna’s Material Stock in Buildings. J Ind Ecol 2017;21:368–80. https://doi.org/10.1111/JIEC.12446.

[4] Lederer J, Gassner A, Keringer F, Mollay U, Schremmer C, Fellner J. Material flows and stocks in the urban building sector: A case study from Vienna for the years 1990-2015. Sustain 2020;12. https://doi.org/10.3390/SU12010300.

[5] Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, et al. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc Natl Acad Sci U S A 2017;114:1880–5. https://doi.org/10.1073/PNAS.1613773114/SUPPL_FILE/PNAS.1613773114.SD01.XLSX.

[6] Augiseau V, Kim E. Spatial characterization of construction material stocks: The case of the Paris region. Resour Conserv Recycl 2021;170. https://doi.org/10.1016/J.RESCONREC.2021.105512.

[7] Lederer J, Gassner A, Fellner J, Mollay U, Schremmer C. Raw materials consumption and demolition waste generation of the urban building sector 2016–2050: A scenario-based material flow analysis of Vienna. J Clean Prod 2021;288:125566. https://doi.org/10.1016/J.JCLEPRO.2020.125566.

[8] Lei H, Li L, Yang W, Bian Y, Li CQ. An analytical review on application of life cycle assessment in circular economy for built environment. J Build Eng 2021;44. https://doi.org/10.1016/J.JOBE.2021.103374.

[9] López Ruiz LA, Roca Ramón X, Gassó Domingo S. The circular economy in the construction and demolition waste sector – A review and an integrative model approach. J Clean Prod 2020;248. https://doi.org/10.1016/J.JCLEPRO.2019.119238.

[10] Akhimien NG, Latif E, Hou SS. Application of circular economy principles in buildings: A systematic review. J Build Eng 2021;38:102041. https://doi.org/10.1016/J.JOBE.2020.102041.

[11] UKGBC. How Circular Economy Principles can impact carbon and value - UKGBC - UK Green Building Council. How Circ Econ Princ Can Impact Carbon Value 2022. https://www.ukgbc.org/ukgbc-work/how-circular-economy-principles-can-impact-

carbon-and-value/ (accessed September 5, 2022).

[12] Eberhardt LCM, Birkved M, Birgisdottir H. Building design and construction strategies for a circular economy. Archit Eng Des Manag 2022;18:93–113. https://doi.org/10.1080/17452007.2020.1781588.

[13] Arora M, Raspall F, Fearnley L, Silva A. Urban mining in buildings for a circular economy: Planning, process and feasibility prospects. Resour Conserv Recycl 2021;174. https://doi.org/10.1016/J.RESCONREC.2021.105754.

[14] Arora M, Raspall F, Cheah L, Silva A. Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. Resour Conserv Recycl 2020;154. https://doi.org/10.1016/J.RESCONREC.2019.104581.

[15] Roemers G, Galle N, Kennedy E. NOTITIE RIJK VAN NIJMEGEN CIRCULAIR Regionale Visie en Uitvoeringsprogramma. 2022.

[16] Gontia P, Thuvander L, Ebrahimi B, Vinas V, Rosado L, Wallbaum H. Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. J Ind Ecol 2019;23:1328–43. https://doi.org/10.1111/JIEC.12939.

[17] Lederer J, Gassner A, Kleemann F, Fellner J. Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna. Resour Conserv Recycl 2020;161. https://doi.org/10.1016/J.RESCONREC.2020.104942.

[18] Opalis. MATERIAL SHEETS REUSE TOOLKIT. 2021.

[19] Rotor LA du SC. Réemploi des matériaux de construction – Recensement des filières et mise en œuvre des pratiques de réemploi en France. ADEME 2022:44.

[20] Wang B, Yan L, Fu Q, Kasal B. A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete. Resour Conserv Recycl 2021;171:105565. https://doi.org/10.1016/J.RESCONREC.2021.105565.

[21] Hossain MU, Poon CS, Lo IMC, Cheng JCP. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resour Conserv Recycl 2016;109:67–77. https://doi.org/10.1016/J.RESCONREC.2016.02.009.

[22] Gharfalkar M, Court R, Campbell C, Ali Z, Hillier G. Analysis of waste hierarchy in the European waste directive 2008/98/EC. Waste Manag 2015;39:305–13. https://doi.org/10.1016/J.WASMAN.2015.02.007.

[23] Gorgolewski M. Designing with reused building components: some challenges. Build Res Inf 2008;36:175–88. https://doi.org/10.1080/09613210701559499.

[24] Addis B. Building with reclaimed components and materials: A design handbook for

reuse and recycling. Taylor and Francis; 2012. https://doi.org/10.4324/9781849770637/BUILDING-RECLAIMED-COMPONENTS-MATERIALS-BILL-ADDIS.

[25] Anastasiades K, Goffin J, Rinke M, Buyle M, Audenaert A, Blom J. Standardisation: An essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry. J Clean Prod 2021;298:126864. https://doi.org/10.1016/J.JCLEPRO.2021.126864.

[26] Gontia P, Nägeli C, Rosado L, Kalmykova Y, Österbring M. Material-intensity database of residential buildings: A case-study of Sweden in the international context. Resour Conserv Recycl 2018;130:228–39. https://doi.org/10.1016/J.RESCONREC.2017.11.022.

[27] Augiseau V, Kim E. Inflows and outflows from material stocks of buildings and networks and their space-differentiated drivers: The case study of the paris region. Sustain 2021;13:1–21. https://doi.org/10.3390/SU13031376.

[28] Luscuere LM. Materials Passports: Optimising value recovery from materials. Proc Inst Civ Eng 2017;170:25–8. https://doi.org/10.1680/JWARM.16.00016.

[29] Kennedy C, Cuddihy J, Engel-Yan J. The Changing Metabolism of Cities. J Ind Ecol 2007;11:43–59. https://doi.org/10.1162/JIE.2007.1107.

[30] Augiseau V, Barles S. Studying construction materials flows and stock: A review. Resour Conserv Recycl 2017;123:153–64. https://doi.org/10.1016/J.RESCONREC.2016.09.002.

[31] OVAM, SPW, Brussels Envionment. FAQ-Utilisation de l'outil TOTEM-Version 2.4 - Update December 2021. 2021.

[32] Hoekman P, Bellstedt C. Urban Material Flows and Stocks Accounting: A Review of Methods and their Application. 2019.

[33] Beloin-Saint-Pierre D, Rugani B, Lasvaux S, Mailhac A, Popovici E, Sibiude G, et al. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. J Clean Prod 2017;163:S223–40. https://doi.org/10.1016/J.JCLEPRO.2016.09.014.

[34] Eberhardt LCM, Birkved M, Birgisdottir H. Building design and construction strategies for a circular economy. Archit Eng Des Manag 2022;18:93–113. https://doi.org/10.1080/17452007.2020.1781588/SUPPL_FILE/TAEM_A_1781588_SM8160.PDF.

[35] Corona B, Shen L, Reike D, Rosales Carreón J, Worrell E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour Conserv Recycl 2019;151:104498.

https://doi.org/10.1016/J.RESCONREC.2019.104498.

[36] Malabi Eberhardt LC, van Stijn A, Kristensen Stranddorf L, Birkved M, Birgisdottir H. Environmental design guidelines for circular building components: The case of the circular building structure. Sustain 2021;13:5621. https://doi.org/10.3390/SU13105621/S1.

[37] EUROSTAT. Economy-wide Material Flow Accounts Handbook | System of Environmental Economic Accounting 2018. https://seea.un.org/content/economy-wide-material-flow-accounts-handbook (accessed January 27, 2023).

[38] Carolin Bellstedt, Gerardo Ezequiel Martín Carreño, Aristide Athanassiadis, Shamita Chaudhry. Urban circularity assessment method - Deliverable 4.4. 2022.

[39] Rosado L, Kalmykova Y, Patrício J. Reprint of: Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. J Clean Prod 2017;163:S254–66. https://doi.org/10.1016/J.JCLEPRO.2017.05.143.

[40] Haas W, Krausmann F, Wiedenhofer D, Heinz M. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. J Ind Ecol 2015;19:765–77. https://doi.org/10.1111/JIEC.12244.

[41] Nußholz JLK, Whalen K. Financial assessment of reusing materials in buildings: Comparing financial potential of wood, concrete, and glass reuse. IOP Conf Ser Earth Environ Sci 2019;225. https://doi.org/10.1088/1755-1315/225/1/012042.

[42] Mayer A, Haas W, Wiedenhofer D, Krausmann F, Nuss P, Blengini GA. Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. J Ind Ecol 2019;23:62–76. https://doi.org/10.1111/JIEC.12809.

[43] Mayer A, Haas W, Wiedenhofer D, Krausmann F, Nuss P, Blengini GA. Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. J Ind Ecol 2019;23:62–76. https://doi.org/10.1111/JIEC.12809.

[44] Ghaffar SH, Burman M, Braimah N. Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. J Clean Prod 2020;244. https://doi.org/10.1016/J.JCLEPRO.2019.118710.

[45] Stephan A, Athanassiadis A. Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resour Conserv Recycl 2018;129:248–62. https://doi.org/10.1016/J.RESCONREC.2017.09.022.

[46] Tanikawa H, Fishman T, Okuoka K, Sugimoto K. The Weight of Society Over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. J Ind Ecol 2015;19:778–91. https://doi.org/10.1111/JIEC.12284.

[47] Lanau M, Liu G, Kral U, Wiedenhofer D, Keijzer E, Yu C, et al. Taking Stock of Built Environment Stock Studies: Progress and Prospects. Environ Sci Technol 2019;53:8499–515. https://doi.org/10.1021/ACS.EST.8B06652/SUPPL_FILE/ES8B06652_SI_002.XLSX.

[48] Gontia P, Thuvander L, Ebrahimi B, Vinas V, Rosado L, Wallbaum H. Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. J Ind Ecol 2019;23:1328–43. https://doi.org/10.1111/JIEC.12939.

[49] Winterstetter A, Heuss-Assbichler S, Stegemann J, Kral U, Wäger P, Osmani M, et al. The role of anthropogenic resource classification in supporting the transition to a circular economy. J Clean Prod 2021;297:126753. https://doi.org/10.1016/J.JCLEPRO.2021.126753.

[50] Adamu M, Bhattarai SR. Evaluation of potential reuse and recycle of residential construction material in the city of Gothenburg . 2022.

[51] Environmental Performance Assessment Method for Construction Works. n.d.

[52] Gassner A, Lederer J, Kovacic G, Mollay U, Schremmer C, Fellner J. Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna. J Clean Prod 2021;311. https://doi.org/10.1016/J.JCLEPRO.2021.127591.

[53] Etude de métabolisme territorial à l ’ échelle du territoire de Rennes Métropole 2022.

[54] Zhou W, Moncaster A, Reiner DM, Guthrie P. Developing a generic System Dynamics model for building stock transformation towards energy efficiency and low-carbon development. Energy Build 2020;224:110246. https://doi.org/10.1016/J.ENBUILD.2020.110246.

[55] Arbabi H, Lanau M, Li X, Meyers G, Dai M, Mayfield M, et al. A scalable data collection, characterization, and accounting framework for urban material stocks. J Ind Ecol 2022;26:58–71. https://doi.org/10.1111/JIEC.13198.

[56] Dai M, Ward WOC, Meyers G, Densley Tingley D, Mayfield M. Residential building facade segmentation in the urban environment. Build Environ 2021;199:107921. https://doi.org/10.1016/J.BUILDENV.2021.107921.

[57] Bianchi M, Tapia C, del Valle I. Monitoring domestic material consumption at lower territorial levels: A novel data downscaling method. J Ind Ecol 2020;24:1074–87. https://doi.org/10.1111/JIEC.13000.

[58] Homepage | Opalis 2022. https://opalis.eu/en (accessed June 9, 2022).

[59] Dealers | Opalis n.d. https://opalis.eu/en/dealers (accessed June 9, 2022).

[60] Lachat A, Mantalovas K, Desbois T, Yazoghli-Marzouk O, Colas AS, Di Mino G, et al. From buildings' end of life to aggregate recycling under a circular economic perspective: A comparative life cycle assessment case study. Sustain 2021;13. https://doi.org/10.3390/SU13179625.

[61] Augiseau V, Barles S. Studying construction materials flows and stock: A review. Resour Conserv Recycl 2017;123:153–64. https://doi.org/10.1016/J.RESCONREC.2016.09.002.

[62] IBO. Oekoindex OI3 - IBO - Österreichisches Institut für Bauen und Ökologie n.d. https://www.ibo.at/materialoekologie/lebenszyklusanalysen/oekoindex-oi3 (accessed June 29, 2022).

[63] Röck M, Sørensen A, Steinmann J, Lynge K, Horup LH, Tozan B, et al. Towards embodied carbon benchmarks for buildings in Europe – Facing the data challenge. 2022. https://doi.org/https://doi.org/10.5281/zenodo.6120522.

[64] Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. EN 15804+A2, 2019.

[65] EUGEOS. EUGEOS' 15804_A2-IA DATABASE: METHOD METHOD. 2022.

[66] Rasmussen FN, Andersen CE, Wittchen A, Hansen RN, Birgisdóttir H. Environmental product declarations of structural wood: A review of impacts and potential pitfalls for practice. Buildings 2021;11:362. https://doi.org/10.3390/BUILDINGS11080362/S1.

[67] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007/S11367-016-1087-8.

[68] Belgian Building Research Institute. The environmental impact of reuse in the construction sector 2021.

[69] Eberhardt LCM, van Stijn A, Rasmussen FN, Birkved M, Birgisdottir H. Development of a Life Cycle Assessment Allocation Approach for Circular Economy in the Built Environment. Sustain 2020, Vol 12, Page 9579 2020;12:9579. https://doi.org/10.3390/SU12229579.

[70] Su S, Li X, Zhu Y, Lin B. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build 2017;149:310–20. https://doi.org/10.1016/J.ENBUILD.2017.05.042.

[71] Pomponi F, Moncaster A. Circular economy for the built environment: A research

framework. J Clean Prod 2017;143:710–8. https://doi.org/10.1016/J.JCLEPRO.2016.12.055.

[72] Hossain MU, Ng ST. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. J Clean Prod 2018;205:763–80. https://doi.org/10.1016/J.JCLEPRO.2018.09.120.

[73] Bertin I, Mesnil R, Jaeger JM, Feraille A, Le Roy R. A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements. Sustain 2020, Vol 12, Page 3147 2020;12:3147. https://doi.org/10.3390/SU12083147.

[74] Luscuere LM. Materials Passports: Optimising value recovery from materials. Proc Inst Civ Eng Waste Resour Manag 2017;170:25–8. https://doi.org/10.1680/JWARM.16.00016.

[75] Product Sustainability (GaBi) Data Search | Sphera n.d. https://sphera.com/product-sustainability-gabi-data-search/ (accessed May 4, 2023).

[76] Inies, reference environmental and health data for buildings and RE2020 - Inies n.d. https://www.inies.fr/en/ (accessed May 4, 2023).

[77] Base carbone® - data.gouv.fr n.d. https://www.data.gouv.fr/fr/datasets/base-carbone-r-1/#/resources (accessed May 4, 2023).

[78] Environmental Performance Assessment Method for Construction Works. n.d.

[79] Startsidan - Boverket n.d. https://www.boverket.se/ (accessed May 4, 2023).

[80] ÖKOBAUDAT n.d. https://www.oekobaudat.de/ (accessed May 4, 2023).

[81] baubook GmbH. Willkommen bei baubook — Deutsch 2023. https://www.baubook.at/zentrale/ (accessed May 10, 2023).

[82] Aparecido Lopes Silva D, Oliveira Nunes A, Aparecida da Silva Moris V, Moro Piekarski C, Oliveira Rodrigues T. How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto CILCA 2017. CILCA, 2017.

[83] openLCA Nexus: The source for LCA data sets n.d. https://nexus.openlca.org/databases (accessed July 13, 2022).

[84] SimaPro | LCA software for informed change-makers n.d. https://simapro.com/ (accessed May 4, 2023).

[85] Ciroth A, Gmbh G. EN15804 add-on the EN15804 add-on for ecoinvent by GreenDelta. Berlin: 2022.

[86] GaBi Software n.d. https://gabi.sphera.com/software/gabi-software/ (accessed July 13, 2022).

[87] Life cycle assessment software for Infrastructure | One Click LCA n.d. https://www.oneclicklca.com/construction/infrastructure-life-cycle-assessment/ (accessed June 2, 2022).

[88] EQUER, logiciel éco-conception bâtiments et quartiers - Mines Paris - PSL n.d. https://www.ces.minesparis.psl.eu/Logiciels/EQUER/ (accessed May 4, 2023).

[89] EVALMETAB n.d. https://www.evalmetab.fr/ (accessed May 4, 2023).

[90] Efficacity - UrbanPrint n.d. https://efficacity.com/quartiers-bas-carbone/nos-logiciels/urbanprint/ (accessed May 4, 2023).

[91] DoTank Circular City Wien 2020 -2030. DoTank Circular City Wien 2020-2030 Ein 10 Jahres Programm der Baudirektion. 2022.

[92] Luger B, Hofman G, Kodydek K, Schrenk C, Roithmayr S. Zirkuläres Wien ! Digitales Booklet zur Fach-Enquete am 3. Juni 2022. 2022.

[93] Bjørn Vidar Vangelsten, Lindeløv B, Nguyen N, Ørding Hansen J, Jensen A, Jacobi N, et al. CIRCULAR CITY INDICATOR SET. 2020.

[94] Bellstedt C, Athanassiadis A, de Groot R, Hellemans A, Malk V, Rodriguez S, et al. Sector-wide circulartiy assessment construction sector. 2021. https://doi.org/https://cityloops.eu/fileadmin/user_upload/Materials/SCA/SCA_Construction_sector_report.pdf.

[95] Heinrich MA. Material flows of the German building sector. Int HISER Conf Adv Recycl Manag Constr Demolition Waste 2017:302–5.

[96] Circular Building Assessment Prototype - BAMB n.d. https://www.bamb2020.eu/post/cba-prototype/ (accessed September 5, 2022).

[97] D4.3: BIM Models and Material Passport of the Spanish and Austrian demos: Demo 1 and Demo 4 WP 4, T 4.1 n.d.

[98] Home - Madaster 2023. https://madaster.com/ (accessed July 19, 2022).

[99] Lozano SM. D4.: Circular economy audit: Baseline calculation for Demo 1 and Demo 4Errore. L'origine riferimento non è stata trovata. Technical References Project Title Innovative circular solutions and services for new business opportunities in the EU housing sector Project Coordinator n.d.

[100] Lanau M, Liu G, Kral U, Wiedenhofer D, Keijzer E, Yu C, et al. Taking Stock of Built

Environment Stock Studies: Progress and Prospects. Environ Sci Technol 2019:8499–515.

[101] Lederer J, Gassner A, Kleemann F, Fellner J. Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna. Resour Conserv Recycl 2020;161:104942. https://doi.org/10.1016/J.RESCONREC.2020.104942.

[102] Gassner A, Lederer J, Fellner J. Material stock development of the transport sector in the city of Vienna. J Ind Ecol 2020;24:1364–78. https://doi.org/10.1111/JIEC.13024.

[103] Gontia P, Thuvander L, Ebrahimi B, Vinas V, Rosado L, Wallbaum H. Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. J Ind Ecol 2019;23:1328–43. https://doi.org/10.1111/JIEC.12939.

[104] Stichting Nationale Milieudatabase. Nationale Milieudatabase | environmental performance of buildings 2023. https://milieudatabase.nl/en/ (accessed July 4, 2023).

[105] Annual average population - STATISTICS AUSTRIA - The Information Manager n.d. https://www.statistik.at/en/statistics/population-and-society/population/population-stock/annual-average-population (accessed February 13, 2023).

[106] Kleemann F, Lehner H, Szczypińska A, Lederer J, Fellner J. Using change detection data to assess amount and composition of demolition waste from buildings in Vienna. Resour Conserv Recycl 2017;123:37–46. https://doi.org/10.1016/j.resconrec.2016.06.010.

[107] Lederer J, Fellner J, Gassner A, Gruhler K, Schiller G. Determining the material intensities of buildings selected by random sampling: A case study from Vienna. J Ind Ecol 2021;25:848–63. https://doi.org/10.1111/JIEC.13100.

[108] Lederer J. [AIT] Stocks and flows models of Vienna for CREATE 2022.

[109] Huuhka S, Kaasalainen T, Hakanen JH, Lahdensivu J. Reusing concrete panels from buildings for building: Potential in Finnish 1970s mass housing. Resour Conserv Recycl 2015;101:105–21. https://doi.org/10.1016/J.RESCONREC.2015.05.017.

[110] ASI. Concrete — Specification, performance, production, use and conformity — Part 1: Rules for the implementation of ÖNORM EN 206 for normal and heavy concrete. Annex E Utilization of recycled mineral aggregates according to ÖNORM B 3140 2018.

[111] Küpfer C, Bastien-Masse M, Fivet C. Reuse of concrete components in new construction projects: Critical review of 77 circular precedents. J Clean Prod 2023;383:135235. https://doi.org/10.1016/J.JCLEPRO.2022.135235.

[112] Rosado L, Lanau M, Wallbaum H, Liu Y, Jacobssonstalheim N. Gothenburg Circular Construction Living Lab 2023.

[113] Augiseau V, Chartier A, Monfort D, Lanau M. Living-lab Rennes description 2023.

[114] Gebetsroither-Geringer E. Klimur - AIT Austrian Institute Of Technology 2022. https://www.ait.ac.at/themen/drc/projects/klimur (accessed February 2, 2023).

[115] Stadtentwicklung Wien MA 21 A - Stadtteilplanung und Flächenwidmung Innen-Südwest. Strukturkonzept Rothneusiedl Herausforderungen und Zielsetzungen für die Entwicklung eines Modellstadtteils für Klimaschutz und Klimaanpassung. Vienna: 2021.