DTU Library

D3.2 Recommendations for improving the capture of material flow data in the built environment

Cartwright, Ben ; Weeks, Caroline ; Lowres, Flavie ; Abis, Marco ; Andersen, Rune; Bromisch, Janus ; Charlson, Andrea ; Haaspuro, Tiina ; Hobbs, Gilli ; Jennings, Tom

Total number of authors:
19

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Deliverable/Milestone	**D3.2 Recommendations for improving the capture of material flow data in the built environment**
Grant Agreement No	821201
Project Acronym	CIRCuIT
Project Title	Circular Construction In Regenerative Cities
Contractual delivery date	31 January 2021 (M20)
Actual submission date	31 January 2021
Dissemination level	Public
Work Package	3
Author(s)	Ben Cartwright, Caroline Weeks & Flavie Lowres *with direct input from* Marco Abis, Rune Andersen, Janus Bromisch, Andrea Charlson, Tiina Haaspuro, Gilli Hobbs, Tom Jennings, Antony Maubach-Howard, Petra Pikkarainen, Vasiliki Savvilotidou, Mette Skovgaard, Kaie Small-Warner, Henna Teerihalme, Martin Tilsted, Eleanor Turner, Daniel Antony van Peer *as well as support from numerous others across the CIRCuIT project.*
Quality assured by	Andrea Charlson
Approved by	Mette Skovgaard
Abstract	In the digital age, the potential benefits of capturing and analysing data are apparent in all areas of urban development. With this recognition, data and digital tools are core areas of research and development within the CIRCuIT project, with outcomes intended to support action both within and outside the project. The knowledge base, however, is currently limited with respect to (a) the possible ways that data can support circular management of built environment material flows, (b) whether the data necessary to support circular management of material flows exists and is of sufficient availability and quality to the relevant stakeholders, and (c) what actions may be taken to fill any gaps in the availability and quality of the necessary data. This report describes the methodology and findings of a research programme that investigated these knowledge gaps. The findings on the availability and quality of data were used to develop recommendations for how data could be improved or applied more effectively by practitioners, researchers, policymakers and other key stakeholders in support of a circular economy of built environment materials within cities.

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Executive Summary

Overview

This report summarises the methodology and findings of a research exercise aimed at understanding existing data and data gaps relating to material stocks and flows within the four CIRCuIT cities (Copenhagen, Hamburg, London and Vantaa/Helsinki region), as well as the methods of collection, format, validation and application. The report also shows the variation in the data availability between the four cities.

The intention of this exercise was to develop recommendations for improving the availability and quality of data to ultimately enable relevant stakeholder groups to make decisions that promote a circular economy of construction materials and waste.

Methodology

Building on the findings of earlier research in Deliverable D3.1, the research methodology consisted of various stages:

- First, an understanding of the actions necessary to improve the circularity of city material flows (use cases) was developed.
- Second, the data required to effectively undertake the identified use cases was defined.
- Third, the availability and quality, as well as the methods of data capture and exchange (where available) of the abovementioned data requirements were evaluated within each city to help identify data gaps and weaknesses.
- Fourth, recommendations were developed that addressed, directly or indirectly, the gaps and weaknesses in the data that was available to the stakeholder groups identified responsible for implementing the use cases. Recommendations were focussed around the creation of data through primary research, the capture of data by practitioners, the promotion of standardised and interoperable of data, the mechanisms of data exchange between stakeholder groups, the integration of data into databases, and the analysis of data.

All stages of the research methodology involved input from the CIRCuIT partners and significant multi-disciplinary and multi-sectoral desk-based research, stakeholder engagement (of both CIRCuIT project partners as well as external actors), and insights obtained from attendance at events and conferences (some of which were organised via WP9).

Findings

The research led to the definition of 29 high-level use cases by which stakeholder groups, from product manufacturers to demolition contractors to policymakers, could modify and enhance the circularity of material flows of cities. A large number of data requirements were

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

identified as necessary or useful to enable the implementation of the use cases (where appropriate, these were grouped to allow brevity). The city data evaluations found that there were significant inadequacies in terms of the existence and quality of these data requirements.

20 overarching recommendations were developed, with a number of suggested actions by which to implement them by relevant stakeholder groups, as well as an indication of which CIRCuIT tasks might consider trialling them.

Next steps

The main work following these recommendations will be to conduct a deeper exploration of how the existing recommendations may be implemented within other CIRCuIT tasks, in conjunction with the corresponding task leads.

In work package 3, these recommendations will be directly fed into and built upon during the developments of the data templates (Task 3.3), city circularity database (Task 3.3), and the data frameworks for demonstrators (Task 3.4). The templates, frameworks and database will serve as the basis for integration of the recommendations made in this report with tasks within work packages 4 to 8 and will be developed in tandem with the corresponding task leads.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

1. Introduction

CIRCuIT is an EU Horizon 2020 research project aiming to support the creation of regenerative cities by promoting and implementing circular construction approaches. Partners from four demonstrator cities – Copenhagen, London, Hamburg and the Helsinki region – are collaboratively working across the entire built environment value chain to bridge the gap between theory, practice and policy related to circular economy, and to showcase the possibilities of circular, regenerative built environments.

The project focusses on:

- Urban mining and reverse cycling (dismantling buildings and the reuse and recycling of materials)
- Extending building life through transformation and refurbishment
- Designing for disassembly and flexible construction

Supporting these core areas are several cross-cutting work packages, including development of:

- Consistent and comprehensive approaches to data collection, analysis and management to support the demonstrators and to enable the aim for moving the concept of buildings as material banks into city scale understanding and implementation (WP3 Map flows of built environment materials, to which this report contributes)
- Replicable recommendations that can support cities in overcoming barriers and implementing circular construction solutions and initiate changes at system level (WP7 Governance, instruments and urban planning approaches)
- A 'Circularity Hub' - an open, accessible data and information platform to support acceptance and implementation of circular construction projects (WP8 Circularity Hub)
- The CIRCuIT Academy, to disseminate project experience, knowledge and deployment practices to cities and the construction industry (WP9 the CIRCuIT Academy)

Decision making related to circular economy relies on information and data to enable informed choices that support the concepts of circularity. A key theme of the CIRCuIT project (Work Package 3) is therefore to assess the nature of information available about materials and their flows through the built environment. In particular, **the aim of this report is to set out recommendations for improving data capture within the practices and constraints of the four CIRCuIT cities and regions**.

It is recognised that the information needed to support circularity in the sector may change over time depending on construction trends, evolving initiatives and drivers. Hence this report should be considered as a baseline from which the sector can evolve, while delivering the most immediate apparent needs.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

The recommendations from this report will be of relevance to a range of construction and built environment stakeholders who will play an important role in improving the information available to the sector, in order to drive a circular economy. These include:

- Product manufacturers and distributors
- Building design teams and consultants
- Project clients (private and public)
- Building / asset / facilities managers
- Demolition contractors
- Waste management organisations
- Reused product brokers
- Planning officers
- City policymakers

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

2. Background - the role of data

Cities are complex, nested systems, which comprise a complex network of sub-systems of interlinked objects and processes, each of which is itself formed of sub-systems (Rosales 2017). In the case of the built environment, the city as a whole is comprised of nested systems such as boroughs, comprising neighbourhoods, comprising buildings and infrastructure, comprising elements, comprising components/products, comprising materials. (Moffat & Kohler 2008). As such, the stocks and flows of materials at the scale of the city system is a function of those occurring within the individual systems at every level of organisation, from materials to city.

The concept of a city as a collection of systems in a nested hierarchy is a vital consideration when trying to achieve circular economy at city-level

However, to understand and manage the system as a whole requires an accurate and granular understanding of the various systems, objects and processes that occur within it, and of their interactions. Without this understanding, it is not possible for decision-makers at any level to identify the key shortfalls and opportunities within their remit. The capture, exchange and application of accurate and robust data is thus essential.

The complex network of interactions between systems and levels of organisation means that the effects of a decision in one system has consequences beyond the system boundary. As such, modifying the circularity of the city requires the availability of as much detailed data on as many relevant systems as possible.

Achieving circularity in the use of resources generated and consumed by a city's built environment sector requires system-level modification of the flows of material resources used in buildings. In practical terms, this modification may be achieved through:

- Avoidance of material flows where they are unnecessary;
- Reduction in the overall material quantities embodied within material flows;
- Replacement of existing material flows with ones that have less negative and more positive impacts;
- More efficient utilisation of existing material flows so that maximal value is obtained, and minimal value wasted; and,
- Looping of existing material flows so that there is a reduced demand for new material inputs to the system.

The flow of resources is influenced by construction stakeholders, who modify the nature of material flows through the decisions they make. For example, they decide what construction products are procured, what designs to incorporate, what waste management approaches to take, what planning requirements to implement, and so on. In an ideal scenario for a circular economy, such decision makers would have access to 'perfect' information on how they could adjust their decisions to help create circular material flows. E.g. a building designer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

would explore data on how different design strategies influence the volume and impacts of materials associated with a building throughout its lifecycle, or a planning policymaker could analyse which parts of the building stock are most suitable for refurbishment or deconstruction based on the relative impacts of the different actions.

With this link between information and decisions in mind, the purpose of the present research was to map out what some of the most important decisions in achieving a circular economy of construction materials were, assess what data was required to support these decisions, and, in cases where the data is insufficient, make recommendations on how to obtain it.

2.1. Data within the CIRCuIT project

Work Package 3 seeks to map the flows of built environment materials within the demonstrator cities and ultimately improve the collection, quality and availability of such data to support circular actions via five tasks:

Task 3.1: Investigate current data on existing built environment and/ or material flows in cities to determine the ‘state of the art’, then offer recommendations for improving data capture.

Task 3.2: Develop a suite of circularity indicators to provide benchmarks for the sector, relevant for material, building and city level, that will ultimately feed into a Circularity Dashboard (WP8). A report on the recommended indicators is forthcoming (D3.3).

Task 3.3: Create data templates to give a standardised framework of data collection required for the planned exploitation and application of data in other work packages (e.g. Circularity Hub, Dashboard, and Materials Exchange Portal). This will be supported by a business case for how such a database can be updated and managed during and beyond the project.

Task 3.4: Develop a data framework for the attributes needed to support, monitor, measure and assess the project’s demonstrator activities, and instigate the required data capture.

Task 3.5: Provide guidance on how to exploit the framework and data at a city level, to support public sector decision making and policy compliance.

This report is based on a state of the art review (Deliverable D3.1[1]) exploring current data availability in cities and providing recommendations on how it could be improved, focussing on the four example CIRCuIT demonstrator cities, but with inevitable EU-wide applicability for some elements.

[1] https://www.circuit-project.eu/post/state-of-the-art-on-material-flow-data-in-the-built-environment-summary-report

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821201

3. Methodology

CIRCuIT report D3.1 mapped the 'state of the art' of data sources available relating to the built environment and/ or material flows in each of the CIRCuIT cities. However, in order to assess the usefulness and completeness of the data and to develop recommendations, it was necessary to first consider how data may be used to promote circularity within the city system.

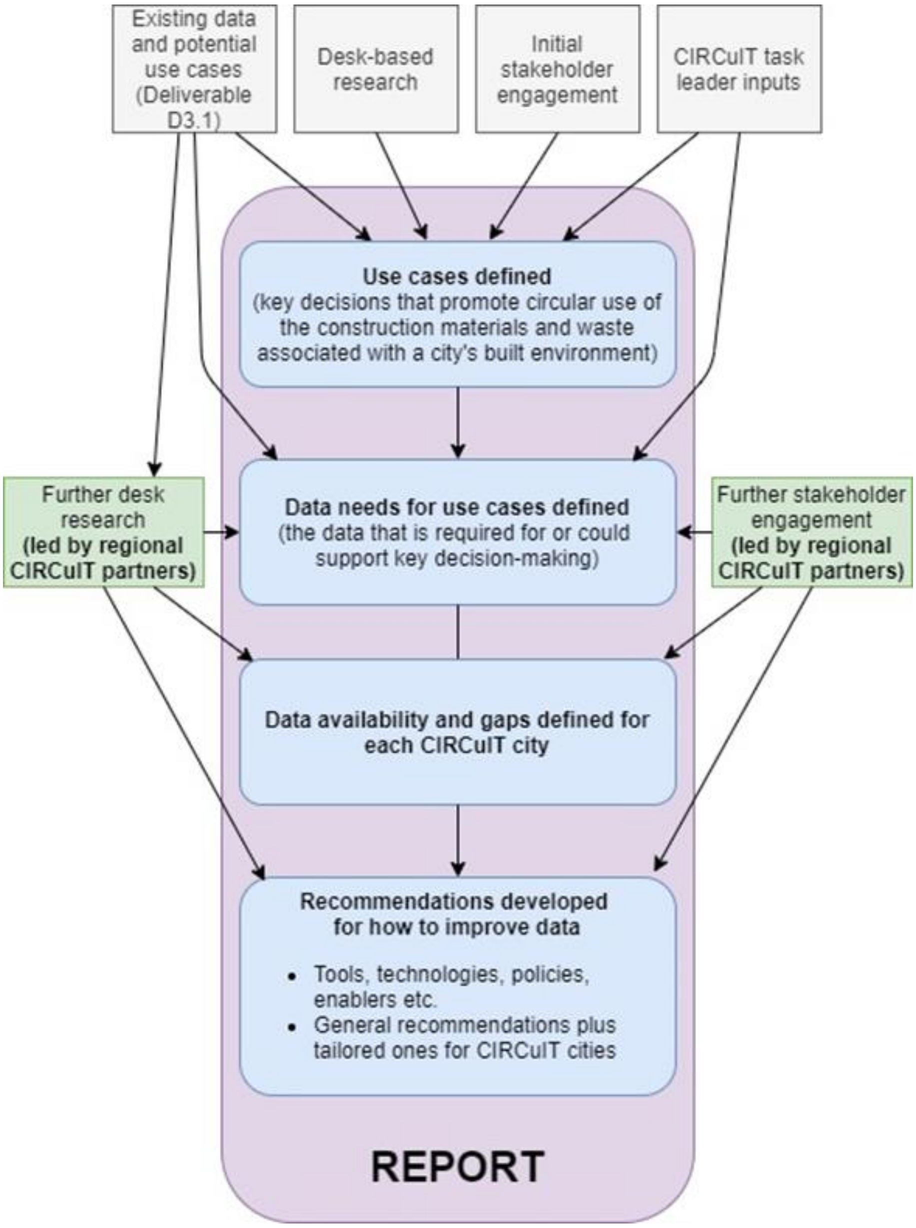
The approach followed for the delivery of this task is described here:

- First, an understanding of the actions necessary to improve the circularity of city material flows (use cases) was developed.
- Second, the data required to effectively undertake the identified use cases was defined.
- Third, the availability and quality, as well as the methods of data capture and exchange (where available) of the abovementioned data requirements were evaluated within each city to help identify data gaps and weaknesses.
- Fourth, recommendations were developed that addressed, directly or indirectly, the gaps and weaknesses in the data that was available to the stakeholder groups identified responsible for implementing the use cases. Recommendations were focussed around the creation of data through primary research, the capture of data by practitioners, the promotion of standardised and interoperable of data, the mechanisms of data exchange between stakeholder groups, the integration of data into databases, and the analysis of data.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

An overview of the task methodology is given in Figure 1 and elaborated below.

Figure 1: Schematic showing research methodology



More details of the different sub-tasks carried out for the delivery of D3.2 are provided in the sections below.

3.1 Development of use cases

The first stage of this research involved consultation with the leaders of the other CIRCuIT work packages as to what activities exist that support built environment circularity that could

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

be enhanced by better data, resulting in an initial set of use cases. Next, a combination of desk-based research and interviews with relevant stakeholders within the built environment sectors of the four CIRCuIT cities was conducted to refine and validate the initial set of use cases.

The use cases were built from the extraction of information from D3.1, an extensive review of academic literature, grey literature, industry initiatives and relevant events across the four CIRCuIT partner countries as well as across Europe. CIRCuIT partners from the four cities also provided input and feedback on the use cases. Finally, industry stakeholders were consulted directly through interviews, helping to develop and validate the use cases.

3.2 Definition of data needs to fulfil use cases

In addition to supplying recommendations for use cases, work package leads were also tasked with indicating the types of data that would be necessary to achieve their suggestions. This activity provided a valuable baseline upon which further desk research and external stakeholder engagement was used for refinement and validation.

4. Assessment of availability and quality of identified data needs

Following the elaboration of the data needs for each use case, an exercise was carried out by researchers in each CIRCuIT city to determine:

a) Whether the required data existed and was readily available to the relevant stakeholders; and,

b) Whether there was any indication of the quality and reliability of any data sources that did exist.

The existence/availability of data was ranked as either 'available', 'sometimes/partially available' or 'not available' using a traffic light approach. In several cases, the availability of data could not be confirmed; researchers had the option to indicate this accordingly.

The quality and reliability of data was judged using a traffic light approach. Issues with data ownership and accessibility often hindered research attempts, and therefore in some cases only third-party opinions or information could be obtained.

Where data was judged to be unavailable or of insufficient quality/reliability, it was identified as a 'data gap'.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

4.1 Provide recommendations for improved data

Following the data needs assessment, recommendations were developed which could help to improve upon the key defined data gaps. These recommendations were mostly framed around the relevant stakeholders who would be able to fulfil or drive the necessary data capture or exchange. Recommendations were developed by conducting desk-based research, obtaining suggestions from CIRCuIT partners, and through interviews with external stakeholders.

Stakeholder interviews were conducted with relevant actors from built environment value networks, in order to validate any recommendations developed through desk-based research and suggestions from other CIRCuIT partners, as well as to develop any new recommendations that might have been missed. A series of questions was developed, centred around the data gaps that had been identified in the previous step. Some questions were relevant to more than one sector stakeholder, while the majority were tailored specifically for the sector group most likely to be involved in the generation or management of the data requirement(s). Only those questions relevant to the stakeholder were asked, to ensure the interviews were focussed and efficient. An overview of the interview questions is included in Appendix 1.

35 interviews were carried out in total for this exercise by CIRCuIT partners, covering each of the cities. Relevant stakeholders were identified in the following sectors:

- Product manufacturers and suppliers
- Building designers and architects
- Clients / developers
- Consultants
- Building / asset / facilities managers
- Demolition contractors
- Waste management organisations
- Reused product brokers
- Planning officers
- City policymakers

The feedback from these interviews was used to shape and validate the final sets of recommendations presented in Table 5 (see section 4.4).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

5. CIRCuIT city data assessments

5.1 Definition of use cases

To judge whether a data source is useful or sufficiently complete requires some context – there must be some consideration of the purpose for which the information is intended to be used. Therefore, potential scenarios or activities that would require data to support decision making have been termed 'use cases' in this study, and can relate to various 'levels' of a City's circular economy, for example:

- At a product level (where data can inform potential product adaptations or material selections)
- At building level (where it may inform modifications to a building's design or to the installation of components, or the relative merits of refurbishment versus deconstruction)
- At a city-wide level (where data could inform the selection of renewal areas, the setting of regulations that encourage reuse or extend the lifespan of materials, products and buildings)

Potential use cases were primarily identified by considering the purposes for which data is needed across the CIRCuIT project work packages. Some additional use cases that are not immediately recognisable as being relevant to CIRCuIT, largely those relating to materials and products, also became apparent from desk-based research and stakeholder engagement. However, their role as the fundamental unit of material flows within city systems means that decision-making at the higher levels of organisation still influences, or is influenced by, the capture and integration of data on materials and products. For example, building a circular building depends in large part on using construction products that themselves have good circular attributes (e.g. they are reused, recycled, reversible and durable) – a prerequisite in this scenario is that data has been captured on the circular attributes of the products being considered, and that this data has been communicated to the project team. Another example could be policymaking to encourage circular building design and management may be supported by a better understanding of which building types in the existing stock have more or less reusable content.

5.2 Development of use cases

The table below summarises the use cases that have been identified as relevant to the CIRCuIT cities and the wider circular economy of the sector, and examples of data that is required to address these. Note that neither the use cases nor the data requirements listed are considered to be an exhaustive summary of the situation within the CIRCuIT cities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Instead, they were developed and used to guide discussion and research into gaps and weaknesses of the availability of data for built environment stakeholders.

All use cases presented are broadly aimed at relevant built environment stakeholders within cities, including those which directly handle and influence material flows (e.g. product manufacturers, contractors, waste management organisations) as well as those with a more indirect or auxiliary influence, such as policymakers, planning authorities or researchers. Most but not all of the use cases are directly relevant to CIRCuIT tasks, however they are all linked through the central theme of achieving circular material flows. For example, the CIRCuIT consortium does not include product manufacturers. However, product-level data is still an essential consideration for building-level actors, policymaking and stakeholders handling materials at end-of-use such as reused product brokers, which are represented in CIRCuIT.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Table 1: List of use cases, with decision-makers groups, rationale for use, and relevance to CIRCuIT tasks

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
Product design and manufacture			
1. Substitute feedstocks in existing construction products	Product manufacturers	Substitution of virgin and remote materials and components for local reused and recycled content within a product means that use of the product will be associated with lower demand for remote and virgin resources. Factors include: • Whether the material or component is reused, recycled or virgin • The distance the material or component is sourced from • The amount of waste generated in the pre-manufacture supply chain	N/A
2. Implement design measures encouraging dematerialisation (product-level)	Product manufacturers	In some cases, products may be designed to minimise the amount of materials used to deliver the end product, whilst ensuring the product's functionality, durability, health and safety, and other important aspects are not negatively affected. Where this is achieved it is known as 'dematerialisation'. For instance: • Some feedstocks may be substituted for others with less waste between extraction and the point of manufacture (e.g. through transport, storage and processing) • Some design features may be excessively bulky, and may be trimmed without impacting on product performance • Certain design approaches (such as the use of CAD/CAM) allow more efficient planning and use of feedstock • Certain design and manufacture approaches (such as offsite manufacture or modular components) mean that any offcuts or by-products may be easily reintroduced to the manufacturing process by the manufacturer	N/A
3. Implement product design attributes that enables future use / life extension of product or part of a products	Product manufacturers	Often, a product can be designed so that it has key features enabling it to deliver more functional use for a longer time within a single use cycle (life extension), or so that it can be reused or recycled with minimal loss of value. For instance, design measures could target reversibility, reusable content, recyclable content, repairability, or durability.	N/A
Alternative product ownership models and Extended Producer Responsibility			
4. Offer products through product-service system models	• Product manufacturers • Product distributors (eg: building merchants)	Some products (depending on service life and level of reversibility from the building) may be specified for buildings without necessarily owning them. Leasing, servitisation, and performance-based models are examples where the product manufacturer or product distributors retains ownership of the physical products while the consumer pays for the use or performance of them. These models allow for manufacturers to undertake dedicated repairs and maintenance on their products due to the availability of feedstock and their understanding of the products.	N/A

[2] Tasks listed under this column are those where the use case being described will be, or could be, implemented, or where the use case is closely linked with the subject matter of the task.

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
5. Implement product end-of-use management (e.g. take-back schemes)	• Product manufacturers • Product distributors (eg: building merchants)	One way that product manufacturers can be given responsibility for the products beyond their factory gates is for them to work with schemes that will promote initiatives for circular management.. For example, the Extended Producers Responsibility (EPR) model from Defra (in the UK) specifies that product manufacturers are responsible for the whole-life impacts of the products they sell, and have duty of care over their post-use stage. The producers must be responsible for recovering and managing their products when no longer required by a consumer (i.e. within a building), and are thus inclined to retain residual value by e.g. reuse, remanufacture and recycling.	N/A
Project client specifications			
6. Require project supplier organisations with certain circularity attributes or experience	• Project clients • Client advisors	Project clients can ensure that any building they create is as circular as possible by using designers, consultants and contractors with capabilities for designing, building and managing buildings for circularity. Additionally, clients can specify that any product suppliers are able to provide reused/recycled and reusable/recyclable products. As well as ensuring that a building is circular, this will help to drive demand for circular economy capabilities within the labour market.	Task 7.2
7. Include requirements for circularity in client requirements for building design and construction	• Project clients • • Building design teams • Consultants	The project client has an outsized influence over the circularity of the building to be constructed through specification of design, specification and project management approaches as outlined in the client requirements (statement of need, strategic brief and project brief), as well as the setting of benchmarks relating to circularity indicators or whole life impacts. In stakeholder engagement carried out as part of task 3.1, a common theme was that while designers and supply chain procurement have some impact over the circularity of the building being developed, they ultimately answer to the demands of their clients. This use case can apply to both public and private clients	Task 7.2
Building design and specification			
8. Implement design measures encouraging dematerialisation (building-level)	• Building design teams • Project clients	A major aspect of a circular economy approach is that the overall demand for materials is reduced. Thereby mitigating the depletion of finite resources and the negative whole life impacts associated with construction material use. Various approaches may be used to achieve dematerialisation of buildings through their design, allowing delivery of the required degree of functionality and performance with reduced material inputs. Additionally, ensuring that the building accommodates materially efficient products as-designed (e.g. through MMC compatibility) can aid with building-level material efficiency.	Tasks 5.3, 6.2, 7.3
9. Procure / specify products with good circularity attributes for installation in building	• Building design teams • Cost consultants • Project clients	The construction products specified for projects have a large influence over a building's contribution to the circular economy. Where possible, products should be specified that are: • Reused or recycled • Reusable and recyclable • Are associated with low levels of supply chain waste • Locally sourced • From renewable sources (where appropriate) The specification of such products improves the circularity of material flows directly, but also drives a market for reused and recycled construction products.	Tasks 4.2, 5.2, 5.3, 6.2, 7.3, 7.5

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
10. Use design for disassembly principles	• Building design teams • Project clients	Design for disassembly means that a building can be deconstructed to minimise damage and value loss of its constituent elements and products at the end of its life. The potential for disassembly of a building will depend in part upon the ability to separate products and materials at the end of the building life. Aspects of building design (e.g. accessibility of product mounting and connections) play an important part in whether products designed to be reversible are reversible in practice.	Task 5.3, 6.2, 7.3, 7.5
11. Use design for Adaptability principles	• Building design teams • Project clients	A building that is designed for adaptability can be easily reconfigured at multiple levels to suit more than one functional use for space. Value is realised through minimisation of underutilised space, and avoidance of premature demolition, ultimately resulting in lower material inputs for the functionality obtained across the building's life course. Adaptability may be specific to alternative functional uses for a building, or it may be general, allowing for unknown alternative uses.	Tasks 5.3, 6.2, 7.3, 7.5
Building construction stage			
12. Implement measures to reduce construction waste generated	• Building design teams • Contractors	A large amount of materials used in construction do not end up in the completed building, but become construction waste. Construction waste may be generated in many ways, including through packaging and offcuts from construction products, overordered materials and clash rectification.. As well as designing for material efficiency (see above), site waste management and supply chain logistics approaches (e.g. just-in-time ordering, reuse of existing structures and materials, and clash detection using BIM) can help to reduce the amount of construction waste generated.	N/A
13. Implement measures to increase proportion of construction site waste that is recycled/reused	• Building design teams • Contractors • Waste management organisations	Often there will be some construction waste that is unavoidable through building design and site waste reduction techniques. In these cases, construction waste can be properly measured and managed to ensure that as much as possible is upcycled or reused.	N/A
14. Install products in manner that ensures reversibility	• Building design teams • Contractors	A crucial aspect of the degree of building reversibility (and therefore its potential for transformation or disassembly at end-of-life) is the way in which its constituent products and elements are installed. Even if a product is easily demountable as designed, it will not be reversible if those responsible for its installation do so without considering demountability, e.g. if they cover the connections, use irreversible adhesive methods etc. Therefore, installers must be aware of the principles of reversibility and have the right skills and tools available to implement it. Ideally, the design of products and buildings should enable reversibility to be easily achieved.	Tasks 5.2, 6.2, 7.5
Building use stage			
15. Implement measures to obtain maximum function / value from in-use building	• Building managers • Building owners • Building users • Consultants • Contractors	The amount of functional use delivered by a building per unit of material input is often lower than it could be. Monitoring the condition of products and elements, and undertaking repairs, maintenance and replacements as necessary can ensure the building performs well for longer. Additionally, buildings are often underutilised throughout their service life. Day-to-day, this may occur because there is unused space some or all of the time. Measures could include: • Maximising useful lifespan of each product through monitoring of realised vs expected performance and need to repair, maintenance and replacements • Optimising use of space to obtain maximal value & function	Tasks 5.2, 5.3, 6.2, 7.2, 7.3, 7.5

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
Building transformation			
16. Carry out building transformation	• Building managers • Building owners • Building users • Consultants • Contractors	At some point, buildings become obsolete and this often leads to replacement (demolition followed by new construction). However, obsolescence is more often based on 'behavioural' rather than physical factors, meaning it becomes used less because demand for the building's functionality or performance (along various environmental, economic and social metrics) is below a level that stakeholders are content with. However, the functionality or performance of an existing building may be returned to an acceptable level through transformation of the whole building or parts thereof, with lower demand for energy and material resources, lower waste, reduced costs, and reduced local impacts compared with building replacement.	Tasks 5.2, 5.3, 7.2, 7.3, 7.5
Urban mining of existing buildings			
17. Predict quantities and value of materials/products available for urban mining within building	• Building owners • Demolition/ deconstruction contractors	Knowing the total proportion of a building's material content that is suitable for recirculation can help those responsible for end-of-life management of the building and its constituent parts set benchmarks for recirculation. Additionally, it can allow for calculations of residual value and impacts (see below). Having information down to the level of individual elements, products and materials within a building can also help to develop plans for repairs, replacements and end-of-life management.	Tasks 4.1, 4.2, 5.3, 7.3, 7.5
18. Plan urban mining approaches to maximise residual value and achieve most positive impacts	• Building owners • Demolition/ deconstruction contractors	Each type of element, component or material within a building is likely to have a different potential for urban mining, based on its reversibility or separability from other products and materials, the local/regional availability of reuse, remanufacture and recycling services for its type, and the market conditions for the reused or recycled items. These factors will help to determine the residual value and lifecycle impacts achievable per product within the building. Understanding these costs and benefits will enable decision-making for each part of the building that is based on the most beneficial outcome and could feed into pre-demolition audits.	Tasks 4.1, 4.2, 5.3, 7.3, 7.5
Options appraisal for existing buildings			
19. Decide whether to replace, transform or leave an existing building as it is	• Project clients • Building owners • Building users • Financers • Planning authority	The costs and benefits associated with transforming or replacing an existing building can vary greatly depending on its characteristics and the local availability of skills, services, its location and urban mining infrastructure. For example, some obsolescent buildings may be very limited in terms of the options for transformation, and to do so would result in a building that is still underutilised and/or badly performing. In this case, it may make more sense to replace the building and maximise urban mining. Alternatively, if the building is performing well and delivering sufficient social and economic benefit in the first place without creating overly negative environmental impacts, there may be no need to take any action other than repairs and maintenance. Depending on the building types, there is also the question of the environmental performance of the the refurbished building in use versus the embodied impact of rebuilding. As per these examples, decision-makers dealing with existing buildings need to understand the various environmental, economic and social costs and benefits associated with different options for a building.	Tasks 4.1, 5.1, 5.2, 5.3, 7.3, 7.5
Existing building procurement			

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
20. Procure buildings with high circular potential	• Property investors and finance brokers • Insurers	Setting criteria for the procurement of buildings with better circularity-related features helps drive a market for circular design and management of buildings. Information on a building's circular economy-relevant aspects also ensures that the building can be managed to ensure that it delivers maximal functional use during one use or across successive uses (via transformation), and that maximal residual value/function is realised by its constituent products at their end-of-use in the building.	Tasks 7.2, 7.3, 7.5
Building stock management policy and planning			
21. Develop policy and planning promoting circular design, construction, operation, and end-of-life management of buildings	• Planning authorities • Environmental regulatory bodies • Developers • Building (portfolio) owners	By analysing big data on building stocks, it could be possible to determine which buildings are underutilised or underperforming. Policy may then be developed to encourage more efficient use of existing buildings through better management or transformation. Additionally, given good enough data, existing building stocks may be analysed in terms of their material composition, reversibility (and thus urban mining potential) and transformation capacity, allowing the development of planning policy that reflects the most circular treatment. For instance, benchmarks for the proportion of demolition waste that is reused or recycled may be developed based on urban mining potential. Or, the demolition of buildings that demonstrate low potential for urban mining, but high transformation capacity could be disincentivised, and so on.	Tasks 7.2, 7.3, 7.5, 7.7
Policy for supply chains and waste management			
22. Develop regulations on product design and manufacture	• Environmental regulatory bodies • Industry associations • Assessment scheme developers	As discussed previously, product design and the feedstocks and processes used in manufacture are key factor in the circularity of material flows. These can ensure that products use reused/recycled materials and components, that there is low waste in the supply chain, that the product delivers maximal functional use throughout their service life, and that they can be reused or recycled at highest possible value at end-of-life. Regulations for product design and manufacture is therefore an important opportunity to drive a circular economy of construction materials.	N/A
23. Develop Extended Producer Responsibility type policy	• Environmental regulatory bodies • Industry associations	The EPR model specifies that product manufacturers are responsible for the whole-life impacts of the products they sell, and have duty of care over them end-of-use. The producers must be responsible for recovering and managing their products following use within a building and are thus inclined to retain residual value by e.g. reuse, remanufacture and recycling.	N/A
24. Develop waste management regulations	• Environmental regulatory bodies • Industry associations	The waste management industry is a key actor group with influence over the circular economy, in particular the looping of end-of-use products through reuse and recycling. Ensuring that the industry implements appropriate targets, benchmarks and approaches is thus an important role for governance.	N/A
25. Plan targeted support and incentives to key circular economy sectors and business models	• Planning authorities • Environmental regulatory bodies • Local government	An important factor in the development of a circular economy is the existence of a market and culture for circular economy-related skills and business models. A role for (local) authorities is therefore to provide support for relevant sectors and businesses, e.g. those involved in selective deconstruction, repairs and maintenance of products or buildings, building refurbishment and transformation, and circular design of products or buildings.	Tasks 7.3, 7.5, 7.7

Use case	Decision-maker group	Description/rationale for use case	Relevant CIRCuIT tasks[2]
Waste infrastructure planning			
26. Plan and invest in waste infrastructure and management resources	• Planning authorities • Environmental regulatory bodies • Local government	Many waste streams require specific types of infrastructure to be reused or recycled; thus, investment should be directed towards infrastructure and jobs that are suited to the predicted types and quantities of CDW that is expected to be generated in the locality or region. For instance, investing in infrastructure for the recycling of a certain type of material would be pointless if there was very little of that material within the building stock that is likely to be demolished in the greatest numbers in the coming decades.	N/A
Marketplace for reused and recycled products			
27. Create a marketplace for reused and recycled construction products	• Building owners • Project clients • Demolition/ deconstruction contractors • Waste management organisations • Material testing and certification organisations	A crucial factor in a circular economy is the existence of a market for locally sourced reused and recycled construction products. On the supply-side, sellers (i.e. the owners of soon-to-be-demolished buildings) require a consistent pool of potential buyers, while on the demand-side, potential buyers need access to a straightforward and reliable supply of products that match their needs without additional hassle or expense (compared with conventional procurement methods).	Tasks 4.1, 4.2, 8.3
Benchmarking, monitoring and visualisation of city circular economy			
28. Visualise data pertaining to circularity of a city's built environment	• Organisations and associations in key industries • Local government • Citizens?	Visualise data pertaining to circularity of a city's built environment depicting material stocks and flows, as well as performance indicators, the locations of important infrastructure and services (e.g. waste management, product testing), and the arisings and requirements of products available for procurement. This could be of use for a wide range of actor groups, both as a visual aid to understand the status of the region's built environment circular economy, and also to identify key opportunities for action.	Task 8.5
29. Carry out benchmarking and target-setting regarding circular economy at city level	• Organisations and associations in key industries • Local government	Monitoring the performance and progress of a city's circular economy and its various facets is important since it improves decision-makers' understanding of how they should focus their efforts and investment to make further progress.	Task 8.4

5.3 Data requirements identified for each use case

The data requirements identified as necessary or useful for undertaking the use cases identified in section 4.2 are displayed in Table 2, below. Table 3 displays the use cases fed into by each data requirement. Some of the identified data sources are of relevance to several use cases, while others may be specific to a single use case. Data may also simultaneously be of use at the various 'levels' of a city's circular economy (i.e. product-, building-, or city-level) and hence consideration needs to be given going forward to how data may be made available to all the stakeholders that require it.

Table 2: Data requirements identified

Data requirement	Reference
Building circularity indicator scores	A
Building information: intended function/performance, design and specifications, installation history, use history, current condition and performance, current use patterns/utilisation rate, external factors (e.g. local area affluence, local trends in space requirements, demolition rate)	B
Capacities and geographic coverage of existing infrastructure, services and skills for management of prioritised waste streams	C
Circular attributes of common building design and construction approaches within building stock (e.g. reuse potential, transformation capacity) for use as a basis for e.g. planning policy	D
Circularity capabilities (indicators) of organisations being considered for employment	E
Current and expected future performance of building in current form	F
Data for modelling: Influence of building circularity indicators on whole life impacts (social, environmental, economic) and whole life costs of building	G
Data for modelling: Typical residual value realised for elements, products or materials, based on type/class, circularity indicators and external system parameters	H
Data for modelling: Typical whole life impacts realised for elements, products or materials, based on type/class, circularity indicators and external system parameters	I
Evidence for effectiveness/impacts for inclusion of circular requirements in public tenders, from previous examples of implementation	J
Existing amount of waste generated between manufacture and construction site	K
Functional and spatial requirements for building to be constructed based on primary use	L
Functional and spatial requirements for possible alternative uses for building in parallel to primary use	M
Guidance: Local marketing opportunities for products after preparation and processing of waste	N
Guidelines for non-destructive reversal/disassembly of products and elements	O
Guidelines for repair and maintenance of products and elements (e.g. necessary actions and their typical timeframes)	P

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Data requirement	Reference
Guidelines on installation techniques to ensure reversibility of products/elements	Q
Key sectors and circular economy business models which demonstrate strong performance or potential to contribute to circular flows of construction materials and waste	R
Listings: Alternative feedstocks to consider for substitution, with indicators of circularity and whole life impacts	S
Listings: Location, type, capacity and contact details of key services and infrastructure for circular treatment of waste materials and products	T
Listings: Organisations utilising circular business models and approaches for construction materials and waste	U
Listings: Product requirements for upcoming projects in region (i.e. in construction, refurbishment, repair and replacement activities)	V
Listings: Products available for specification - quantity, physical properties & condition, location, value and circularity indicators	W
Listings: Products/materials soon to be released from projects in region and available for direct reuse (e.g. construction, refurbishment or demolition waste) - quantities, physical properties & condition, location, value and circularity indicators	X
Listings: Spare/surplus products, product components and materials available within region	Y
Location, condition and performance of in-use products (to allow efficient repairs and maintenance, as well as predictive maintenance)	Z
Mass of recyclable materials not within reusable products or their components in existing building	AA
Mass of reusable products and product components in existing building	AB
Material inputs and waste attributed to individual feedstocks or design and manufacture approaches	AC
Material inputs to and outputs from building stocks (split by building stock segment - historical, current, predicted)	AD
Projected local/regional demand for space and functionality	AE
Predicted construction waste to be generated / materials to be released from project, split by material type/waste stream (based on building attributes and materials/waste management approaches)	AF
Product circularity indicator scores (including cradle-to-gate material inputs and waste)	AG
Product types and design variants responsible for greatest proportion of material consumption, or impacts associated with material consumption, within region's construction sector	AH
Sectors responsible for greatest proportion of material consumption and/or waste (plus impacts thereof) within region's construction and buildings sector	AI
Projected generation of different CDW streams in region	AJ

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Data requirement	Reference
Projected future product/material demand in city/region (up to 20 years, split by product/material class)	AK
Real-time condition and performance of individual products/elements in building	AL
Real-time performance, condition and usage data for buildings in the building stock	AM
Required building performance	AN
Required properties of product (e.g. durability, thermal)	AO
Size of, and impacts associated with, existing CDW flows, split by CDW stream	AP
Structure of CDW chains (i.e. what actors handle what waste streams and in what quantities)	AQ
Total quantities of different material and product types embodied within building stock of interest	AR
Type, quality and condition of waste materials and end-of-use products being handled	AS
Typical rate of reuse/recycling for different product/material types	AT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Table 3: Data requirements as they relate to use cases

	Data requirement reference (see table 2)																																												
Use Case	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
Product-level use cases																																														
1. Substitute feedstocks in existing construction products								x	x										x					x	x				x				x								x					
2. Implement design measures encouraging dematerialisation (product-level)								x	x										x										x				x	x							x					
3. Implement product design attributes that enables future use / life extension of product								x	x																								x	x			x				x					
4. Offer products through product-service system models		x						x	x						x	x	x								x	x							x					x								
5. Implement product end-of-use management (e.g. take-back schemes)		x						x	x						x	x	x			x		x				x							x					x								
Building-level use cases																																														
6. Require project supplier organisations with certain circularity attributes or experience					x																x																									
7. Include requirements for circularity in client requirements for building design and construction		x				x	x			x											x																			x						x
8. Implement design measures encouraging dematerialisation (building-level)	x	x				x	x						x										x									x	x	x						x						
9. Procure / specify products with good circularity attributes for installation in building	x	x					x	x	x				x										x	x	x							x	x	x			x			x						x
10. Implement Design for Disassembly	x	x					x						x																				x							x						
11. Implement Design for Adaptability	x	x					x						x	x																	x		x							x						
12. Implement measures to reduce of construction waste generated	x	x					x																									x	x												x	x

	Data requirement reference (see table 2)																																												
Use Case	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
13. Implement measures to increase proportion of construction site waste that is recycled/reused	x	x					x							x						x		x										x	x												x	x
14. Install products in manner that ensures reversibility	x																x																x													
15. Implement measures to obtain maximum function / value from in-use building	x	x			x	x	x					x	x		x	x	x								x	x												x		x						
16. Carry out building transformation	x	x				x	x																								x		x							x						
17. Predict quantities and value of materials/products available for urban mining within building	x	x						x	x						x												x	x				x	x					x								x
18. Plan urban mining approaches to maximise residual value and achieve most positive impacts	x	x						x	x					x	x					x		x					x	x				x	x				x	x								x
19. Decide whether to replace, transform or leave an existing building as it is	x	x				x	x	x	x					x	x	x				x		x					x	x			x	x	x				x	x		x						x
20. Procure buildings with high circular potential	x	x		x		x	x	x	x				x																																	
City-level use cases																																														
21. Develop policy and planning promoting circular design, construction, operation, and end-of-life management of buildings				x			x													x										x						x	x	x	x					x		x
22. Develop regulations on product design and manufacture							x	x																					x				x	x	x	x	x									x
23. Develop Extended Producer Responsibility policy									x									x																	x	x	x					x				
24. Develop waste management regulations			x					x	x											x															x	x						x	x			x

	Data requirement reference (see table 2)																																												
Use Case	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
25. Plan targeted support and incentives to key circular economy sectors and business models																		x		x															x		x									
26. Plan and invest in waste infrastructure and management resources			x															x		x														x		x	x					x	x	x		x
27. Create a marketplace for reused and recycled construction products		x					x	x	x											x		x		x				x				x	x					x			x				x	
28. Visualise data pertaining to circularity of a city's built environment			x																			x		x						x						x	x		x			x		x		x
29. Carry out benchmarking and target-setting regarding circular economy at city level			x																	x		x														x	x					x		x		x

5.4 Data availability and gap analysis

Following the investigation of potential use cases and the identification of subsequent information required to support them, Table 4 summarises the high-level analysis carried out by the research teams in each city to assess the availability of that data in London, Hamburg, Copenhagen and Helsinki/Vantaa.

Some of the major issues and barriers identified from the data availability analysis, and which are common across the four CIRCuIT cities include:

- **Inadequate bottom-up data capture and/or data sharing.** A principal finding from our analyses was that, for many of the identified use cases, the data required to achieve it is not currently created. This may be because the data capture does not occur in the first place, however it is also true that a great deal of potentially useful data is captured but not made available for analysis and utilisation due to a lack of incentives or privacy concerns. There exists a general scarcity of data in built environment sectors that has only been flagged as a major hindrance to the industry in recent years. This scarcity means that even data that is easy to capture, and which could be highly useful for a range of purposes including circular economy, is not captured. Currently, a fully data-driven, digital-first approach is still mostly limited to large frontrunner organisations, and circular economy related application/rationale is yet to factor significantly into their data-related activities.
- **Issues with data quality and validity.** it was often difficult to identify any indication of validity or quality of data available. For instance, bills of quantities can be obtained by exporting data from BIM models (and thus could assist with calculations of building-level urban mining potential), however this data often does not reflect what happened on site. City-level waste data is another area where data quality is questionable based on a lack of a lack of mechanisms for monitoring and validation, a pattern which is broadly repetitive across CIRCuIT cities.
- **Lack of data transparency and data exchange.** One finding which came out in many cases was that the data necessary to support a use case may in fact exist but is not made available by the holder of that data. In these instances, the relevant data is often not shared simply because there is no motivation for providers to do so. It may be difficult to persuade potential data suppliers to carry out additional data capture when there is no tangible benefit to them. As well as an absence of incentives, data exchange is also hindered by a lack of understanding by the would-be data user that it exists and is available. A final barrier to data exchange is that the data fields, formats and software programs used vary significantly within and between stakeholder groups, especially where the groups operate at different levels of organisation within the city system (e.g. product manufacturers and construction project contractors), or at opposite ends of a value chain (e.g. product manufacturers and waste management organisations).
- **Lack of data on available resources to enable circularity.** Across cities it was identified that for a stakeholder wanting to take action to promote the circular economy, there is little information on the key resources (i.e. products and services) that could be decided upon based on attributes that favour circularity, from the procurement of reused

or recycled feedstocks for product manufacture to listings of organisations providing key services for urban mining from a building at end-of-life.

- **Lack of quantitative data for measuring and monitoring circularity.** While approaches for measuring the circularity of products, buildings and whole cities have been and continue to be developed, the actual data necessary to underlie these indicators is often not available, and to capture this data would in many cases require substantial additional effort. Fundamentally, understanding and managing the material circularity of a system, whether a building, an organisation or a city, relies on having some idea of the quantities and pathways of the materials that flow through it. Aside from waste data, there is currently no data available on material stocks and flows in any of the cities and for most of the buildings and organisations within them.
- L**ack of data on the impacts of actions that promote circular economy.** A major drawback of the existing data was that it is not possible for stakeholders to model and compare the likely impacts of different decisions they could make (such as product specifications, design features, or waste management protocols) on material circularity and whole life impacts. This is in large part due to the relatively early stage of primary research in this field; to obtain quantitative values for these requires significantly more research, both experimental as well as observational (the latter of which would ideally make use of large datasets on materials and buildings throughout their lifecycles).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Table 4: Data gaps and weaknesses by CIRCuIT city

Note, the analysis has been represented as a 'traffic light' system of green, yellow, red and grey, to reflect data availability as follows:

- Green: data is currently captured and is available to the relevant stakeholder
- Yellow: the data is either only partially captured or under some circumstances, or it is captured but is not easily available to the relevant stakeholder
- Red: the data is not currently captured
- Grey: it was not able to determine whether the data was captured or available

Data requirement		**Availability/quality in each region**			
Ref	*Description*	*Copenhagen*	*Hamburg*	*London*	*Vantaa*
A	Building circularity indicator scores	Red	Red	Yellow	Red
B	Building information: design and specifications, installation history, use history, current condition and performance, current use patterns/utilisation rate, external factors	Yellow	Yellow	Yellow	Yellow
C	Capacities and geographic coverage of existing infrastructure, services and skills for management of prioritised waste streams	Green	Yellow	Yellow	Yellow
D	Circular attributes of common building design and construction approaches within building stock for use as a basis for e.g. planning policy	Red	Red	Red	Red
E	Circularity capabilities (indicators) of organisations being considered for employment	Yellow	Yellow	Yellow	Yellow
F	Current and expected future performance of building in current form	Green	Red	Yellow	Red
G	Data for modelling: Influence of building circularity indicators on whole life impacts (social, environmental, economic) and whole life costs of building	Red	Red	Yellow	Grey
H	Data for modelling: Typical residual value realised for elements, products or materials, based on type/class, circularity indicators and external system parameters	Yellow	Red	Red	Red
I	Data for modelling: Typical whole life impacts realised for elements, products or materials, based on type/class, circularity indicators and external system parameters	Red	Red	Red	Yellow
J	Evidence for effectiveness/impacts for inclusion of circular requirements in public tenders, from previous examples of implementation	Yellow	Grey	Grey	Yellow
K	Existing amount of waste generated between manufacture and construction site	Grey	Yellow	Yellow	Red
L	Functional and spatial requirements for building to be constructed based on primary use	Green	Green	Green	Green
M	Functional and spatial requirements for possible alternative uses for building in parallel to primary use	Yellow	Grey	Yellow	Grey

Data requirement		Availability/quality in each region			
Ref	*Description*	*Copenhagen*	*Hamburg*	*London*	*Vantaa*
N	Guidance: Local marketing opportunities for products after preparation and processing of waste				
O	Guidelines for non-destructive reversal/disassembly of products and elements				
P	Guidelines for repair and maintenance of products and elements (e.g. necessary actions and their typical timeframes)				
Q	Guidelines on installation techniques to ensure reversibility of products/elements				
R	Key sectors and circular economy business models which demonstrate strong performance or potential to contribute to circular flows of construction materials and waste				
S	Listings: Alternative feedstocks to consider for substitution, with indicators of circularity and whole life impacts				
T	Listings: Location, type, capacity and contact details of key services and infrastructure for circular treatment of waste materials and products				
U	Listings: Organisations utilising circular business models and approaches for construction materials and waste				
V	Listings: Product requirements for upcoming projects in region (i.e. in construction, refurbishment, repair and replacement activities)				
W	Listings: Products available for specification - quantity, physical properties & condition, location, value and circularity indicators				
X	Listings: Products soon to be released from projects in region and available for direct reuse (e.g. construction, refurbishment or demolition waste)				
Y	Listings: Spare products and their components available within region				
Z	Location, condition and performance of in-use products (to allow efficient repairs and maintenance, as well as predictive maintenance)				
AA	Mass of recyclable materials **not** within reusable products or their components in existing building				
AB	Mass of reusable products and product components in existing building				

Data requirement		**Availability/quality in each region**			
Ref	*Description*	*Copenhagen*	*Hamburg*	*London*	*Vantaa*
AC	Material inputs and waste attributed to individual feedstocks or design and manufacture approaches				
AD	Material inputs to and outputs from building stocks (split by building stock segment - historical, current, predicted)				
AE	Projected local/regional demand for space/functionality of buildings (up to ~10 years)				
AF	Predicted construction waste to be generated / materials to be released from project, split by material type/waste stream (based on building attributes and materials/waste management approaches)				
AG	Product circularity indicator scores				
AH	Product types and design variants responsible for greatest proportion of material consumption, or impacts associated with material consumption, within region's construction sector				
AI	Sectors responsible for greatest proportion of material consumption and/or waste (plus impacts thereof) within region's construction and buildings sector				
AJ	Projected generation of different CDW streams				
AK	Projected future product/material demand in city/region (up to 20 years, split by product/material class)				
AL	Real-time condition and performance of individual products/elements in building				
AM	Real-time performance, condition and usage data for buildings in the building stock				
AN	Required building performance				
AO	Required properties of product (e.g. durability, thermal)				
AP	Size of, and impacts associated with, existing CDW flows, split by CDW stream				
AQ	Structure of CDW chains (i.e. what actors handle what waste streams and in what quantities)				

Data requirement		Availability/quality in each region			
Ref	*Description*	*Copenhagen*	*Hamburg*	*London*	*Vantaa*
AR	Total quantities of different material and product types embodied within building stock of interest				
AS	Type, quality and condition of waste materials and products being handled				
AT	Typical rate of reuse/recycling for different product/material types				

6. Recommendations

Table 5 provides an overview of the recommendations developed through desk-based research, discussions with CIRCuIT project partners, and stakeholder engagement.

The recommendations are categorised as follows:

- **Recommendations on data creation through research.** While some data to support circular economy use cases could be obtainable through better data capture and exchange by industry practitioners (i.e. material handlers), there are some that cannot be obtained without primary experimental or observational research. These recommendations are thus intended to fulfil gaps in the knowledge which cannot be obtained fully through novel data capture and exchange by practitioners 'in the field'.
- **Recommendation on capture of data by practitioners.** The single recommendation under this category is intended to ensure that any data gaps which could be filled by practitioners with influence over material flows, are filled by them. Note that this recommendation does not provide a direct set of instructions for what data must be captured, by who and through what means; this information will be developed fully in Task 3.3, based in part on the circularity indicators developed as part of Task 3.2.
- **Recommendations on data standardisation and interoperability.** As highlighted in section 4.4, a major drawback of much existing data on buildings and materials is the lack of standardisation and interoperability, which hinders a fluid transfer of data and ultimately limits data exchange and integration, an important means by which stakeholders could obtain information for decision-making. These recommendations are thus aimed at setting the foundation for easier exchange of data between different stakeholder groups (e.g. product manufacturers and building design teams), as well as making it easier to obtain and interpret data for analysis.
- **Recommendations on exchange of data between stakeholder groups.** As discussed previously, many of the gaps in the available data required to support the identified use cases could be more easily obtained (i.e. by avoiding duplication of efforts) through the handover of data between relevant stakeholders, achievable through data sharing frameworks and Common Data Environments. These recommendations are therefore intended to address how to exchange the necessary data.
- **Recommendations on integration of data into databases.** These recommendations are focused on the integration and collation of data from materials, projects and buildings at all points in their lifecycles and use cycles, from cradle to grave. The resulting databases would be highly useful for city-level analytics supporting benchmarking, strategy and policymaking (e.g. those to be developed within CIRCuIT work packages 7 and 8).
- **Recommendations on data analysis.** These are intended to serve as examples of the types of analyses that could be carried out on existing data (where available), in support of circular economy decision-making. They are mostly focused around the type of analysis that would support CIRCuIT tasks, however, are also applicable more broadly.

Ideally (although not necessarily) they would be achieved via analysis of the databases described in the ‘Recommendations on integration of data into databases’.

For each recommendation, a description/rationale is provided, along with the sources upon which the recommendation was inspired, the data requirements from section 4.3 that it would provide, some suggestions actions for implementation, any stakeholder groups that would be responsible for these actions, and the CIRCuIT tasks that the recommendation could feed into. Note that ‘Actions for implementation’ are not all intended as recommended activities within CIRCuIT tasks. Where all or part of the recommendation could fit within the scope of a WP or task in CIRCuIT, this was identified in the table below in the column called “relevant to CIRCuIT task”.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821201

Table 5: List of recommendations

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
Recommendations on data creation through primary research							
1	Develop a methodology for calculating reuse potential of a component or element whilst in-use, based on available data	Currently it is not easy for stakeholders such as asset owners or prospective reused material procurers to understand the reuse potential of their building parts once demolished/ disassembled. Research is therefore required to derive an approach to this.	• Stakeholder engagement • Desk-based review (see e.g. BAMB project[3] outputs, Digital Deconstruction project[4]; Rose & Stegemann 2018; Akanbi et al 2017)	G, H, I, AA, AB, AF, AG, AS	• Conduct primary experimental and observational research to determine typical reuse potentials for common components/elements depending on their relationship with the surrounding system • Develop a process for detecting and extracting this from BIM data (see work by Dr Elma Durmisevic, e.g. the ongoing Digital Deconstruction project)	• Researchers • Industry practitioners (as a collaborator and/or source of data)	• 4.2 • 6.2 • 7.2 • 7.3
2	Develop a methodology to predict the potential residual value of materials, components and elements at end-of-use, based on available data	Currently it is not easy for stakeholders such as asset owners or prospective reused material procurers to understand the value they are likely to obtain from their building parts once extracted from the building. Research is therefore required to derive an approach to this.	• Stakeholder engagement • Desk-based review (see e.g. BAMB project[5] outputs, Digital Deconstruction project[6]; Jabeen 2020)	A, H, W	• Conduct primary experimental and observational research • Trial approaches to determining residual value, considering all end-of-use costs (see e.g. Jabeen, 2020) as well as typical sale price (obtained via analysis of a database e.g. Ref 13)	• Researchers • Industry practitioners (as a collaborator and/or source of data)	• 4.2 • 6.2 • 7.2 • 7.3
3	Develop a methodology for automatic calculation of building/spatial transformation capacity based on available data	Transformation capacity is difficult to assess quantitatively without significant effort. Being able to easily quantify how transformable it is would allow for decision-making over whether to attempt to transform a building, to replace it, or to leave it as it is.	• Stakeholder engagement • Desk-based review (see e.g. Cavalliere et al 2019; Blok & Teuffel 2019)	A, B, D, G, H, I	• Conduct primary research and collection of data into the relative influences of different building attributes on transformation capacity. This could be through experimental research, or through analysis of observational data. Broadly, this could be achieved via: • Analysis of aggregated BIM data (or similar)	• Researchers • Industry practitioners (as a collaborator and/or source of data)	• 5.1 • 7.2 • 7.3

[3] https://www.bamb2020.eu/
[4] https://www.bim-y.com/digitaldeconstruction
[5] https://www.bamb2020.eu/
[6] https://www.bim-y.com/digitaldeconstruction

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
					• Typology-based statistical approach – note that this has been commenced by Copenhagen cluster		
4	Develop LCA, LCC and social impact factors at product and building level that can incorporate the whole life impacts of transformation, urban mining, and Design for Disassembly and Adaptability.	This could be used to model and compare the whole life impacts of different approaches or specifications, or to inform decisions on whether to refurbish a building, demolish it or leave it as it is. This could also help to inform retrofit strategies at city scale based on costs and benefits variable by building type and context.	• CIRCuIT Task 5.3 • CIRCuIT Task 7.5 • Stakeholder engagement • Desk-based review (see e.g. Densley Tingley & Davison 2012; Akbarnezhad, Ong & Chandra 2014)	G, H, I, J, T, AH, AI, AO	• Capture and analysis of primary experimental data and/or observational data sourced from industry e.g. via Material Stock & Flow Database (Ref 13) and Building Stock Database (Ref 14) • Possibility to create a distinct database of environmental/ social/ financial impact factors for common materials, products and material/product classes, for integration with modelling (e.g. modelling of lifecycle costs using BIM, see e.g. Zanni et al 2019)	• Researchers • Industry practitioners (as a collaborator and/or source of data)	• 4.2 • 5.3 • 6.2 • 7.2 • 7.3 • 7.5
5	Develop methodologies for quantifying the reuse potential / transformation capacity of materials, components, elements and buildings within a <u>building stock</u>	Once recommendations 1 to 4 have been achieved, and given appropriate data on the building stock, it could be possible to quantify the reuse potentials/ residual values of materials, components and elements currently embedded in the building stock, and the transformation capacity of buildings. Combined with LCA/LCC/ social value modelling, this could assist with decision-making over how to manage different segments of the building stock for optimal environmental, social and economic outcomes.	• CIRCuIT Task 5.1 • Stakeholder engagement • Desk-based review (see e.g. Blok & Teuffel 2019)	D, AQ, AO	• Obtain granular building stock data to conduct component-level Material Flow Analysis • Combine with research into the reuse potential and residual value of different material, product and element types, and the building transformation capacity indicators, and the lifecycle impacts thereof, as assessed through Refs 1-4	• Researchers • Industry practitioners (as a collaborator and/or source of data)	• 4.2 • 5.1 • 6.3 • 7.2 • 7.3 • 7.5 • 8.3 • 8.4 • 8.5
Recommendations on capture of data by practitioners							
6	Capture data relevant to circular economy according to circularity data templates	As described in section 5.4, there are many gaps in existing data that hinder the ability to carry out the use cases of section 5.2 fully. Capturing data according to standardised data	• CIRCuIT Task 3.3 • Stakeholder engagement	A, B, L, M, O, P, Q, S, AC, AE, AF, AG, AK, AL, AM, AN, AR.	• Relevant practitioners should capture data according to the standardised data templates (Ref 2) that correspond with their remit (i.e. material, product, building or city	• Any practitioner who can capture the data required.	• 3.3 • 3.4 • 3.5

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		templates (see Ref 8) is therefore a way to achieve this.	• Desk-based review (see e.g. Heinrich & Lang 2019; CB23 platform[7])		level), and which contain data fields addressing the data gaps identified in section 5.4.	• *Materials and products:* extractive industries, manufacturers and distributors, any material/ product handler at subsequent lifecycle stages; • *Buildings:* this could include designers, consultants, contractors, facilities managers, surveyors etc. • *City data:* likely to require aggregation of data from material-/product- and building-level sources (potentially through integrated databases, see Refs 13 and 14) • Any data captured should be stored in such a way as to be easily shared with any other stakeholders whose decision-making may benefit from it (see Refs 9, 10, 11)	• Demon-strator activities (4.2, 5.2, 6.2) • 4.1 • 5.1 • 5.3 • 7.3 • 7.5 • 8.3 • 8.4 • 8.5
Recommendations on data standardisation and interoperability							

[7] https://platformcb23.nl/english

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
7	Develop and mainstream the use of circularity indicators	Indicators enable the consistent measurement of circular economy approach	• CIRCuIT Task 3.2 • Stakeholder engagement • Literature review (see e.g. EU Circular Economy Monitoring Framework[8]; Verlcasteren, Christis & Van Hoof 2018; Schoenmakere & Gillabel 2017)	A, AG, D, E, G, H, I, S, AA, AB, AC, AD, AG, AS	• Create/standardise indicators of circular economy performance at the level of materials/products, buildings, organisations, cities and economies • Implement indicators and use them to guide decision making around e.g. procurement, design, construction, end-of-life material flow management, etc. • Apply governance measures that mandate or incentivise the use of indicators for stakeholders responsible for implementation	• *Creation:* researchers, standards bodies • *Policy support:* planning officers, policy makers • *Implementation:* ○ Product handlers (all product lifecycle stages) ○ Building designers/ contractors/ owners/ managers/ end-of-life ○ Organisational operations management ○ City data/ circular economy officers	• 3.3 • 3.4 • 3.5 • Demon-strator activities (4.2, 5.2, 6.2) • 7.2 • 7.3 • 7.5 • 8.5
8	Develop and mainstream the use of circularity data templates at multiple levels	Data templates should be developed that identify what data is necessary to support circular action in the built environment, across stakeholder groups at different levels of organisation, and are made available for use by the relevant stakeholders. Ultimately this would facilitate the capture and exchange of data to support the identified use cases, and would enable the integration of	• CIRCuIT Task 3.3 • Stakeholder engagement • Literature review (see e.g. Acerbi & Taisch 2020; LEXiCON project[9])	A, B, C, F, K, L, M, Z, AA, AB, AE, AG, AK, AL, AM, AN, AR,	• Templates should be created targeting different stakeholder groups with influence over material flows, that address the data gaps identified in section 5.4 (as well as any others that arise through further research). • These should be standardised using data semantics, ontologies, taxonomies and formats that are	• *Creation:* researchers, standards bodies • *Policy support:* planning officers, policy makers; City data/ circular economy officers • *Implementation:*	• 3.3 • 3.4 • 3.5 • Demon-strator activities (4.2, 5.2, 6.2)

8 https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework
9 The LEXiCON project is a collaboration between the UK's Construction Products Association and the Construction Innovation Hub which aims to "support international best practice for the creation and management of product data by standardising the production, use, and management of product data". See https://www.constructionproducts.org.uk/our-expertise/technical-and-regulatory-intelligence/digitalisation/lexicon.

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		relevant datasets into circularity databases (see Refs 3 – 5), which may be analysed to develop insights on how to manage materials, buildings and cities to promote circularity. Standardisation and interoperability are absolutely essential in this pursuit, to allow for the exchange of data between stakeholder groups at different levels of organisation and at different points in material lifecycles; as such, common semantics, ontologies and taxonomies are important to develop.			applicable to all stakeholder groups across material and building lifecycles. • Governance support/ incentivisation for adoption of indicators • Implementation same as indicators (see ref 7)	○ Product handlers (all product lifecycle stages) ○ Building designers/ contractors/ owners/ managers/ end-of-life ○ Organisational operations management	• 7.2 • 7.3 • 7.5 • 8.5
9	Develop / mainstream data exchange methodologies for integration of material and product data with building data and vice versa.	Currently, there is typically little ability to carry-through material/product data to Building Information Models upon installation, and from BIM models to subsequent data management systems upon the material or product's deinstallation from the building. Without this 'golden thread' of data from cradle-to-cradle or cradle-to-grave of a material, it is less easy for subsequent material/ product handlers to understand the origin and circular economy-related attributes and to make decisions that promote circularity.	• Stakeholder engagement • Literature review (see e.g. Aram & Eastman 2013; Mangialardi et al 2017; Halstenburg, Lindow & Stark 2017)	A, B, F, K, L, M, AA, AB, AG, AM, AN, AR	• Develop standards and frameworks enabling the seamless exchange of useful data in standardised formats, at all stages through the material lifecycle • Cooperation between product-level researchers & industry, building-level researchers & industry, and waste/reuse stakeholders • Ideally, Product Lifecycle Management data (via product data management systems) could feed directly into a corresponding BIM object and vice versa, via standardised and machine-readable data fields and interoperable formats and software programs.	• Standards organisations • Research and technology organisations	• Demon-strator activities (4.2, 5.2, 6.2)
Recommendations on exchange of data between stakeholder groups							
10	Material traceability: Capture data on each unit of material, component or element throughout its lifecycle,	This would create a 'golden thread' of material data, allowing for accurate and transparent measurement and modelling of circularity and whole life impacts at any point in the material lifecycle. As	• Stakeholder engagement • Desk-based review (see e.g. Oberti & Paoletti	A, B, K, O, P, Q, W, X, Z, AA, AB, AC, AF, AG, AK, AQ, AR	• Material handlers capture data according to defined data templates (see Ref 8) • Ideally, this should start at material extraction, with data added to	• Any material handler at any point in the material lifecycle: ○ Raw material extraction	• 3.3 • 3.4 • 3.5

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
	and store it in a digital record for transfer	a result, procurement manager for example could calculate exactly how specifying a particular product impacts the whole life impacts of their project. Relevant data may include material passport data, as well as composition, circularity indicators, and any other circular economy-related information.	2020; Copeland & Bilec 2020; Swift et al 2017)		material passports for as long as it is in use (and, where appropriate, combined or integrated with other data for as long as it is in use, for example in Product Data Management or BIM). • Trial / implement emerging technologies such as Internet of Things and RFID tagging to link physical object with their digital representation (Iacovidou et al., 2018) • Data may be uploaded to the Material Flow Database (see Ref 13) – the use of blockchain / Distributed Ledger Technology may be of use to achieve this (see Li, Greenwood & Kassem 2019)	○ Product manufacturer ○ Product distributor ○ Construction product procurement ○ Product users / facilities managers ○ Pre-demolition auditors ○ Demolition / deconstruction contractors ○ Waste management ○ End-of-use materials testing and certification ○ Onward supply chains of reused and recycled products & materials	• Demon-strator activities (Tasks 4.2, 5.2, 6.2)
11	Create, update and handover BIM models to relevant stakeholders depending on building lifecycle stage	BIM models will be essential in circular economy since they allow the storage and sharing of data useful for circular decision-making between relevant stakeholders. Additionally, given appropriate data on the impacts of a product, design or logistical method, they may be used to model the whole life impacts different project approaches through integration of LCC/LCA and social impact assessment approaches	• Stakeholder engagement • Desk-based review (see e.g. van den Berg & Durmisevic 2017)	A, B, F, L, M, O, P, Q, V, X, Z, AA, AB, AF, AG, AL, AN, AS	• If no BIM model exists, create one and capture as much circular economy data as possible ○ NB: there are currently difficulties with assigning parametric variables to BIM objects, however there are ways to overcome this ○ NB: development of methodologies for rapidly generating BIM data through scanning and computer vision is a promising avenue of research that could lead to substantial efficiencies in this field (see e.g. Czerniawski & Leite 2020; Lu et al 2019)	• Designers, architects, consultants • Contractors (product installers) • Facilities managers / Operations & Maintenance contractors • Refurbishment contractors (product installers) • Pre-demolition auditors	• Demon-strator activities (4.2, 5.2, 6.2)

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
					• Where available, attach materials and product data to their corresponding BIM objects according to circularity data templates (see Ref 8) • Hand over BIM model to relevant stakeholders who may need to query it for information they can use to make support decision-making around circular economy; to ensure a Common Data Environment and a single source of truth, this could be achieved using a cloud-based database (Charef & Emmitt 2020) • Whatever lifecycle stage, update BIM model with data relevant to circular economy; the precise data fields that may be updated at different stages will be elaborated further in Task 3.3. Note that data entry may be manual or automatic, e.g. fed in from Internet of Things devices or sensors in an in-use building (Volk, Stengel & Schultmann 2014)	• Demolition contractors	
Recommendations on integration of data into databases							
12	Create a database of services and facilities assisting with circular economy of the built environment	A live geospatial database that provides stakeholders with information on the capacity, availability and location of relevant services such as refurbishment designers and contractors, pre-demolition auditors, selective deconstruction contractors, materials testing and recertification, storage and redistribution, waste recyclers, and reused product sellers. This could follow the example of the	• Stakeholder engagement	C, E, R, T, U, AQ	• Ensure relevant services and facilities capture data on their operations (including specific capabilities such as selective demolition, or particular material streams processed) in a standardised, comparable manner • Collate data and present in a database along with location information; ensure that data is easily interpretable by relevant stakeholders such that they can use	• City data officers within city government • Waste infrastructure planners • Organisations providing relevant services and facilities	• 3.3 • 4.1 • 4.2 • 6.3 • 8.3 • 8.4 • 8.5

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		London Waste Map[10] (and its underlying database), expanded to include all services and facilities of use to the circular economy, with live or regularly updated data, that may be readily integrated into the management systems of stakeholder groups who may have use for it.			it to make decisions on services or facilities to use • Implement policy or incentives to encourage / mandate (where possible) the sharing of open data by relevant actors		
13	Create a live database of material stocks & flows database	A city level database that records where materials are stocked and how they flow throughout the city system, including data of relevance to circular economy such as whether materials are reused or what their typical sale prices are. If aggregated and analysed, this would be an invaluable resource for planning and policymaking to enable city-level Material Flow Management (including waste management), as well as for other applications, for example prospective material sellers being able to understand the likely market value of their assets post-demolition. Given appropriate data security and privacy protocols, this database could also double as a basis for a material traceability database allowing material procurers to have a transparent view of the origin, history and circularity indicators of the materials or products they are procuring. Given sufficient development of methods such as those in Refs. 1 to 11 to enable	• CIRCuIT Task 3.3 • Desk-based research (see e.g. Rose & Stegemann 2019; Gepts et al 2019; Kleemann et al 2017; Copeland & Bilec 2020; UK National Materials Datahub[11]) • Stakeholder engagement (note: as well as D3.2 interviews and attendance at events, webinars etc., this was also flagged in various workshops conducted for circularity indicators as part of D3.3)	H, I, K, S, V, W, X, Y, Z, AD, AH, AJ, AK, AL, AP, AQ, AR, AT	• Two main approaches: 1. Inference of material flows based on building stock characteristics dynamics (see e.g. Gepts et al 2019; Kleemann et al 2017), imports data, waste data and so on 2. Direct measurement of material flows through material traceability approach to data capture • Capture standardised data on materials in a machine readable and interoperable format, following standardised data templates (Ref 8) • Utilise material tracking and traceability approaches to capture 'live' data on materials throughout their lifecycle from cradle to cradle to grave, including locations, use patterns, performance, condition, etc (see Ref 10). This would be the optimal solution since it would allow for true big data analytics, however the large volumes and constant inflows of data involved in this	• *Capture/supply of data:* Any stakeholder that handles or captures information on materials at any point in their lifecycle: extractive industries, product manufacturers and distributors, quantity surveyors, contractors, asset managers, pre-demolition auditors, demolition contractors, quality and condition testing organisations, etc. • *Mandate/ incentivisation of data supply:* City authorities, planning depts.	• 3.4 • 3.5 • 4.1 • 4.2 • 5.1 • 6.2 • 7.3 • 8.3 • 8.4 • 8.5

[10] https://maps.london.gov.uk/waste/

[11] A "single version of truth for materials information in the UK, open for public good", see https://datasciencecampus.github.io/projects/DSC-69-National-Materials-Datahub/. Also see Velenturf (2020).

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		prospective estimation of reusable components within a building planned for demolition, this database could also serve as the basis for the Material Exchange Portal (Task 8.3; see discussion in Charef & Emmitt 2020) and feed into the Circularity Atlas (Task 8.4) and Dashboard (Task 8.5).			approach would likely require that the database be federated or fully decentralised (e.g. using Blockchain) • Could in theory be combined with Building Stock Database (see Ref 14) • Creation and ongoing maintenance of database • Governance support, e.g. policies or incentives for practitioners to capture and supply relevant data to database – see e.g. London Circular Economy Statement		
14	Create a live building stock database	Assuming development of the approaches described in Refs 6, 7, 8, 9 and 11, an accurate, granular and up-to-date understanding of the state, dynamics and circular potential of the building stock is possible. This could include data on the existing building stock, as well as predictive or modelling capabilities regarding the future of the building stock. Such a database could inform decision-making and strategy by planning officers and policymakers as to how to modify patterns of construction, refurbishment, demolition etc to achieve the best social, economic and environmental outcomes. It could also serve as a source of information on available/required materials for the Material Exchange Portal, and would also allow visualisation and benchmarking of building stock circularity in the Circularity Atlas and Dashboard.	• CIRCuIT Task 3.3 • Desk-based review (see e.g. Hudson 2018; Rose & Stegemann 2019)	D, G, V, W, X, AD, AF, AJ, AM, AR, AT	• Define the data that would be useful to capture to allow for management of building stocks • Two broad and potentially complementary approaches to capture data on building stock at one point in time: ○ Upload of project and building (BIM) data by building-level stakeholders, in a machine readable and interoperable format (to be developed in data templates) – this approach could permit a live representation of the building stock close to the 'ground truth' ○ Assumptions-based approach using combination of existing building stock datasets to determine likely building attributes based on typological features • Creation and ongoing curation of database	• *Capture/supply of data:* Any stakeholder that handles or captures information on buildings at any point in their lifecycle	• 3.3 • 3.4 • 3.5 • 4.1 • 4.2 • 5.1 • 6.2 • 6.3 • 7.3 • 8.3 • 8.4 • 8.5

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		(Note: there is an overlap between this and the material flow database at the points that materials flow into and out of buildings)			• Governance measures to support data capture and supply, e.g. policies, incentives or industry agreements and guidance		
Recommendations on analysis of databases							
15	Quantify and predict rates of circular economy-related building stock dynamics, e.g. new construction on greenfield sites, demolition and replacement, transformation, design for disassembly and adaptability in new construction, urban mining (reuse and recycling), etc.	Understanding the existing rates of building stock dynamics, as well as more detailed information such as the typical efficiencies, financials and impacts associated with different approaches, is useful for developing strategies, benchmarks and policies that decision-makers in cities' construction and buildings sectors can use to guide their actions. The creation of city-level baselines against which to measure the efficacy of demonstrator projects is a key aspect of Task 4.1. Additionally, understanding the current and/or future demand for certain building types can increase the utilisation rate and increase time until behavioural obsolescence of a building (whether at new construction stage or upon transformation), meaning that more value is obtained with less resource consumption and waste.	• CIRCuIT Task 4.1 • CIRCuIT Task 5.2 • Desk-based review (see e.g. Huuhka & Lahdensivu 2014; Sartori et al 2008; Kurvinen et al 2021)	C, D, F, G, J, L, R, V, AC, AD, AE, AH, AJ, AK, AR, AT	• Analyse aggregated data on building stocks and the material stocks and flows associated with them via the building stock database (Ref 14) and the material flow database (Ref 13). For example, predictive models may be used to develop a better understanding of future building stock dynamics based on projected demand trends (Kurvinen et al 2021).	• Researchers	• 4.1 • 4.2 • 5.1 • 5.2 • 7.2 • 8.4 • 8.5
16	Quantify and predict stocks and flows of (reusable/ recyclable) materials, components and elements from building stock	Understanding the profile and quantities of different building materials, components and elements within, and that are projected to emerge from, the building stock, can inform strategies and policies around recycling, reuse and building stock management. For example, investment in recycling infrastructure may be directed towards facilities and capabilities for those materials	• CIRCuIT Task 4.1 • Stakeholder engagement • Desk-based review (see e.g. Lanau & Liu 2020; Muller, 2006; Heeren & Hellweg	X, AD, AJ, AP, AR, AT	• Conduct Material Flow Analysis to determine quantities of materials, components and elements in different building stock segments • Quantify recyclable and reusable portions of stocks by, where possible, combine with understanding of A) typical recycling efficiency for the material type, or B) typical reuse potential of	• Researchers	• 4.1 • 7.2 • 7.3 • 8.3 • 8.4 • 8.5

Ref	Recommendation	Description	Source	Data Requirements addressed	Actions for implementation	Responsible stakeholders	Relevant CIRCuIT tasks
		that are expected to emerge in significant quantities and/or which are expected to have the most prominent impacts. Another example would be combining this approach with recommendation Ref 17 to predict the optimal building stock segments to target for retrofit strategy based on the embodied carbon emissions (via the materials involved in retrofit) against the operational carbon savings achievable through retrofit.	2018; Kleemann et al 2017)		components and elements (see Ref according to the construction type or building typology they are embedded within, • Combine with building stock survival analysis (see e.g. Heeren & Hellweg 2018) to determine projected quantities of (reusable) components and elements arising • Research into reuse potential and residual value of different materials, components and elements within the building stock; apply reuse potential, residual value etc. values to existing material stocks determined through MFA		
17	Quantify and predict demand for reused and recycled products	Understanding the demand for reused and recycled products can allow prioritisation of which building stock segments may be demolished and those for which demolition should be avoided, based on both the proportions of recyclable and reusable parts within them, as well as the level of demand for those parts	• CIRCuIT WP4 • Stakeholder engagement	H	• Analyse demand based on aggregated data on sales of building products • This could come from 'traditional' data sources such as economic data (though this is not readily available for reused and recycled products); a better approach could be to tag sale price data to reused/recycled materials through the material traceability approach (Ref 10), and then analyse aggregated sale price data for reused and recycled products via the material stock and flow database (Ref 13)	• Researchers	• 4.1 • 7.2 • 7.3 • 7.5 • 8.4 • 8.5

7. Next steps

Following the development of these recommendations, project partners from all relevant tasks across the CIRCuIT project will be engaged to conduct a deeper exploration and evaluation of the potential for implementation or trialling of the data-focussed recommendations discussed in this report (as well as others where they emerge). The output of this next step discussion will be used to develop and refine sets of data fields to be included in:

1. The database being developed in work package 3 (Task 3.3), which will serve as a repository for data to be analysed and applied to the various CIRCuIT tasks for which data is useful (including, but not limited to, Tasks 4.1, 5.1, 6.3, 7.2, 7.3, 7.5, 8.3, 8.4, and 8.5). Building on the outcomes of the Buildings As Material Banks (BAMB) project, data templates will be also be developed at material, product, space, building and city level – these will set out the fields, units and formats by which data is to be fed into the database in support of the relevant applications, and will include data to feed into circularity indicators (as developed in Task 3.2).

2. The data frameworks (Task 3.4), which will be used by project partners for monitoring, impact measurement and development of benchmarks based on the demonstrator projects. Note that data captured according to the frameworks will also be fed into the Task 3.3 database and will therefore conform to the data templates being developed, and serve as the basis for circularity indicators on the demonstrator projects.

References

Acerbi F & Taisch M (2020). Towards a data classification model for circular product lifecycle management. *Product Lifecycle Management Enabling Smart X. PLM 2020. IFIP Advances in Information and Communication Technology* **594**, Springer, Cham.

Akanbi LA, Oyedele LO, Akinade OO, Ajayi AO, Delgado MD, Bilal M & Bello SA (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation & Recycling* **129**, 175-186

Akbarnezhad A, Ong KCG & Chandra LR (2014). Economic and environmental assessment of deconstruction strategies using building information modelling. *Automation in Construction* **37**, 131-144.

Aram S & Eastman CM (2014). Integration of PLM Solutions and BIM Systems for the AEC Industry. *Proceedings of the 30th ISARC, Montréal, Canada,* 1046-1055.

Bergsdal H, Brattebø H, Bohne RA & Müller DB (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research & Information* **35**(5), 557-570.

Blok R & Teuffel PM (2019). Demolition versus transformation, “mortality of building structures” depending on their technical building properties. *IOP Conference Series: Earth and Environmental Science* **225**, 012016.

Cavalliere C, Dell’Osso GR, Favia F & Lovicario M (2019). BIM-based assessment metrics for the functional flexibility of building designs. *Automation in Construction* **107**, 102925.

Charef R & Emmitt S (2020). Uses of Building Information Modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production* **10**,124854.

Czerniawski T & Leite F (2019). Automated digital modeling of existing buildings: A review of visual object recognition methods. *Automation in Construction* **113**, 103131.

Densley Tingley D & Davison B. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building & Environment* **57**, 387-395.

Gepts B, Meex E, Nuyts E, Knapen E & Verbeeck G (2019). Existing databases as means to explore the potential of the building stock as material bank. *IOP Conference Series: Earth & Environmental Science* **225**, 012002.

Halstenburg FA, Lindow K & Stark R (2017). Utilization of product lifecycle data from PLM systems in platforms for Industrial Symbiosis. *14th Global Conference on Sustainable Manufacturing, GCSM.* Stellenbosch, South Africa.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821201

Heeren N & Hellweg S (2018). Tracking construction material over space and time: Prospective and geo-referenced modeling of building stocks and construction material flows. *Journal of Industrial Ecology* **23**(1), 253-267.

Heinrich M & Lang W (2019). *Material Passports: Best Practice.* Buildings As Material Banks (BAMB). TU

Hudson P (2018). Urban characterisation; Expanding applications for, and new approaches to building attribute data capture. *The Historic Environment: Policy and Practice.* **9**(3-4), 306-327.

Huuhka S & Lahdensivu J (2014). Statistical and geographical study on demolished buildings. *Building Research & Information* **44**(1), 73-96.

Iacovidou E, Purnell P & Lim MK (2018). The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution? *Journal of Environmental Management* **216**, 1-10.

Jabeen I (2020). *Economic feasibility of reusing structural components.* (Unpublished Master's thesis). TU Delft: Delft, Netherlands.

Kinnaird C & Geipel M (2018). *Blockchain Technology: How the Inventions Behind Bitcoin are Enabling a Network of Trust for the Built Environment*. ARUP. Available at: https://www.arup.com/publications/research/section/blockchain-technology (Accessed: January 2021).

Kleemann F, Lederer J, Rechberger H & Fellner J (2017). GIS-based analysis of Vienna's material stocks in buildings. *Journal of Industrial Ecology* **21**(2), 368-380.

Kurvinen A, Saari A, Heljo J & Nippala E (2021). Modeling building stock development. *Sustainability* **13**(2), 723.

Lanau M & Liu G (2020). Developing an urban resource cadaster for circular economy: A case study of Odense, Denmark. *Environmental Science & Technology* **54**(7), 4675-4685.

Li J, Greenwood D & Kassem M (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction* **102**, 288-307.

Lu Q, Chen L, Li S & Pitt M (2020). Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation in Construction* **115**, 103183.

Mangialardi G, Di Biccari C, Pascarelli C, Lazoi M & Corallo A (2017). BIM and PLM associations in current literature. *IFIP International Conference on Product Lifecycle Management*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Moffat S & Kohler N (2008). Conceptualizing the built environment as a social-ecological system. *Building Research & Information* **36**(3), 248-268.

Oberti I & Paoletti I. Da. Ma. Tra: Material Traceability Database. In *Digital Transformation of the Design, Construction and Management Processes of the Built Environment* 2020, 85-93. Springer, Cham.

Rosales N (2017). How can an ecological perspective be used to enrich cities planning and management? *Revista Brasileira de Gestão Urbana* **9**(2), 314-326.

Rose CM & Stegemann JA (2019). Characterising existing buildings as material banks (E-BAMB) to enable component reuse. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability* **172**(3), 129-140.

Sartori I, Bergsdal H, Müller DB & Brattebø H (2008). Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100. *Building Research & Information* **36**, 412-425.

Schoenmakere M & Gillabel J (2017). *Circular by design: Products in the circular economy.* European Environment Agency. Luxembourg: Publications Office of the European Union.

Swift J, Ness D, Kim K, Gelder J, Jenkins A & Xing K (2017). Towards adaptable and reusable building elements: Harnessing the versatility of the construction database through RFID and BIM. *Proceedings of the UIA Seoul World Architects Congress, Seoul, Korea.*

Van den Berg MC & Durmisevic E (2017). BIM uses for reversible building design. *3rd International Green Design Conference 2017: Vital Cities and reversible Buildings for circular economy*. Mostar, Bosnia and Herzegovina.

Velenturf A (2020). *The National Materials Datahub Can Improve Governance for Better Material Use by Industry: An Evidence Briefing from the Resource Recovery from Waste Programme.* UK: Resource Recovery from Waste.

Vercalsteren A, Maarten C & Van Hoof V (2018). *Indicators for a circular economy.* SUMMA. Available at: https://circulareconomy.europa.eu/platform/sites/default/files/summa_-_indicators_for_a_circular_economy.pdf (Accessed January 2021)

Volk R, Stengel J & Schultmann F (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction* **38**, 109-127.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Zanni M, Sharpe T, Lammers P, Arnold L & Pickard J (2019). Developing a methodology for integration of whole life costs into BIM processes to assist design decision-making. *Buildings* **9**, 114.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201

Appendix 1: Stakeholder engagement format and excerpt

- To mitigate interviewee fatigue, interviewers were instructed to ensure interviews lasted no longer than 45 minutes
- Questions and answers in green rows are examples of those focused on the development or validation of use cases, while those in white rows are examples of those exploring the availability/quality of data, methods of data capture, and the exchange processes of data.

Stakeholder group	Example questions
All stakeholder groups	Would it be useful to have access to a database of products/services demonstrated to benefit circular economy? • What stakeholders would be most appropriate to hold and supply this data (manage the database)? • How would you expect them to demonstrate their credentials?
	Thinking about how data can be transferred across a whole building lifecycle, from product data, through construction stage, in-use stage, refurbishment stage to building end-of-life – should/could this data be publicly available?
Building / facilities managers	An awareness of the ongoing condition of building components is also expected to be valuable to inform future reuse options and support alternative procurement models, such as leasing of components. Do you agree this is important and something that asset managers would be responsible for?
	Thinking about how data can be transferred across a whole building lifecycle, from product data, through construction, condition (at any point in time in use), in readiness for retrofit or deconstruction...What method(s)/ format do you believe would be best for this?
Clients/ developers	When setting specifications for projects/development, what sources would you typically rely on to advise on appropriate standards/ criteria to set or best practice approaches (e.g. guidance, listings)?
	Do you have any suggestions on information that could improve this?
Construction firms / contractors	Do you feel there is a need for other types or sources of information to help you reduce site waste and increase upcycling/ recycling on projects?
	Do you record information on the products and materials embodied within existing buildings? If so, how is this done and what do you do with this data?
	What sort of data do you need to support the use of more reclaimed material in new buildings?
Demolition contractors, reclamations and representative bodies	If you were aiming to achieve the highest possible rates of materials recovery and recycling (and value) from an asset… Do you feel that selective demolition/ deconstruction is practical? What are the barriers?
	What information would be essential/beneficial to receive to optimise materials recovery upon demolition/ deconstruction?
	What information do you currently have access to about upcoming demolition projects?
Designers, consultants	Do you agree or disagree that considering the installation of products to be reversible and allow for future recovery is part of the role of the designer, or instead someone else, e.g. contractor?
	What sources of information do you already use (or are needed) to determine whether products or materials you may propose to use in a construction have future reuse potential?
National governments	What policy or regulatory levers could be implemented to encourage stakeholders to capture materials data? (What mechanisms could be easier to

Stakeholder group	Example questions
	implement (e.g. set up voluntary initiatives, set requirements on public projects), what may be more difficult but more impactful, e.g. setting Planning conditions, or EPR requirements)
Product manufacturers	Have you investigated whether there are opportunities in your product manufacture or its installation (via guidance to customers) to improve future reuse or recyclability?
	How could data support circular business models with regard to products?

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821201