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Circular Renovation of Urban Infrastructures: A Multi-Project Perspective

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Abstract
The construction sector is a significant contributor to global waste. With growing concerns about sustainability, adopting circularity in construction projects has become increasingly important. The urban infrastructure sector has characteristics that present valuable opportunities for circularity. This research explores these opportunities by focusing on the renovation of urban infrastructure components through a multi-project perspective. This innovative approach in the field of circular economy reveals new possibilities for material reuse by integrating material flows across multiple projects. By identifying the supply and demand of secondary materials, designers can incorporate them during the redesign phase. Additionally, the synchronization of project phases can be optimized in advance, as material donors and receivers are pre-determined. This research contributes to the field of circular renovation in construction. Project planners, municipalities, designers, contractors, and other stakeholders involved in the renovation process can leverage this novel approach to enhance the circularity and sustainability of their projects. The outcomes of this research can therefore contribute to the goal 12 (responsible consumption and production) and 9 (industries, innovation and infrastructure) of sustainable development goals. This paper presents the initial results and outcomes of a PhD journey. The methods and results will be demonstrated in later studies.

Keywords
Circular renovation, Multi-projects, Urban infrastructure

1 Introduction

The construction sector is known as one of the main waste-creating sectors globally. Construction and demolition industry generates the largest waste stream, and it is responsible for 37.5 % of waste produced in Europe in 2020 (Eurostat statistics). All stages of a building's life cycle—construction, maintenance, renovation, and demolition—generate environmental impacts and produce waste (Mohammadiziazi and Bilec, 2023). As a result, considering sustainability in the construction industry has become essential.

To enhance sustainability in the construction projects, circular economy (CE) principles can be applied. CE is significantly recognized as a better alternative for the linear (take-make-dispose) economic model (Ghisellini et al., 2016). CE is identified as an optimal strategy for construction and demolition waste management (Rayhan and Bhuiyan, 2024). The aim of CE is to minimize the extraction of raw materials from the environment and keeping materials in the cycle as long as possible (Akanbi et al., 2019). CE is often confused with sustainability. Sustainability is the overarching goal, while the circular economy serves as a pathway to achieving a more sustainable economy (Anastasiades et al., 2020).

The term "construction" is broad and encompasses both building structures and various forms of infrastructure. The construction industry is classified into residential and non-residential sectors. Bridges, roads, and other infrastructure are categorized as non-residential construction (Chaudhery., et al., 2022). While several research studies have focused on residential construction (building industry), non-residential construction has been barely addressed. Existing studies in the construction industry have predominantly focused on residential projects, as these are easier and more cost-effective to analyse. Furthermore, their shorter life spans compared to infrastructure projects make them more practical subjects for research (Li et al., 2020). According to a literature review on material stocks in the built environment, out of 249 publications, only a few focused on road (20 publications) and rail (20 publications) infrastructures, while the majority concentrated on the building sector (Lanau et al., 2019). Most CE literature focuses more on the private sector than on public, such as infrastructure, showing a significant research gap (Coenen et al., 2023; Klein et al., 2022).

The urban infrastructure sector has characteristics that may offer new opportunities for circularity; however, these have not been extensively explored in scientific literature. Urban infrastructure elements, such as bridges and quay walls, often have similar material compositions and structural designs. In the urban infrastructure projects, the construction and demolition operations are usually carried out by familiar agents who usually share interests and manage different construction sites in parallel (Smeyers et al., 2022). Therefore, the interaction between project teams can be facilitated. Additionally, infrastructure is primarily owned and financed by public organizations, unlike buildings, which are typically owned by individuals (Dominguez et al., 2009). Public organizations or governments, as owners of infrastructure assets, adhere to strict regulations and have clear missions and goals (Hueskes et al., 2017). For instance, if the government's objective is to promote circularity, it can mandate that contractors and engineering firms comply with these regulations and objectives. These factors suggest potential for innovative circularity approaches specific to public infrastructure. The urban infrastructure components are highly resource-intensive (Coenen et al., 2023; Ecorys, 2016) and their quantity in cities is substantial. The environmental impacts of public civil infrastructure projects are significantly greater than those of residential and commercial projects (Wu et al., 2014) which necessitates further investigation into infrastructure projects.

In the construction sector, multiple renovation projects often occur simultaneously. Scholars have addressed these multi-project networks from planning and scheduling perspectives (Dargahi Darabad et al., 2024; Ekeskär et al., 2022; Ghoroqi et al., 2023; RezaHoseini et al., 2021), however, exploring circularity within such a multi-project network is a novel approach that remains unexamined in existing literature. In this complex network, combining circularity with reverse logistics in the urban context introduces additional complexities. These concepts highlight a research gap that requires further investigation. Therefore, this study focuses on the circular renovation of urban infrastructures from a multi-project perspective and investigates how the circularity can be improved in these projects. Implementing circular supply chain management (CSCM) in such renovation projects presents both significant opportunities and challenges, necessitates the need for a comprehensive investigation of this process.

This research aims to explore the opportunities associated with implementing circularity in the renovation of urban infrastructure components, adopting a multi-project perspective. This multi-project perspective is innovative in the circular economy field, as it reveals new opportunities for material reuse by combining material flows from multiple projects. Moreover, the approach presented in this study is process-based rather than material-based solutions. In addition, this study integrates the concept of circularity with urban logistics, enabling the assessment and reduction of operational carbon emissions while promoting circularity. Overall, this research has the potential to enhance the overall circularity level of the renovation projects, offering broader sustainability benefits than isolated projects. This study can therefore contribute to the field of circularity in the urban infrastructure by developing a new approach for renovation of urban infrastructure.

2 Literature Review

2.1 Renovation process

The renovation process is inherently complex, and integrating circularity adds further challenges. A sustainable renovation comprises several stages, each requiring specific tools and methodologies. Rather than relying on a single comprehensive tool, it is preferable to use a structured methodology that incorporates various tools for different stages (Thuvander et al., 2012). According to a systematic literature review by Timm et al., (2023) on circular economy strategies in construction, the first stage is planning. Similarly, Fernandes & Ferrão, (2023) propose a framework for circular refurbishment, where the initial stage is mapping the building's current state, including geometry and quality assessment. Movaffaghi & Yitmen, (2023) highlight that in dynamic circular economy frameworks, inventory-taking is the first step to identifying reusable materials. While these frameworks focus on buildings, the same principle applies broadly to construction: planning and mapping serve as essential first stages in any circular renovation. This stage is critical for gathering necessary information to guide the renovation process. Various approaches can be employed at this stage, including the waste index (Jalali, 2007), building information modeling (Cheng and Ma, 2013) and image recognition (Yu et al., 2019). The choice of approach depends on the available data for each project.

Following the planning, it is necessary to assess the reusability of materials obtained during the renovation process. The reusability of building materials is influenced by different factors like environmental (Viitanen et al., 2010), financial (Nazemi et al., 2024) and management factors (Kibert et al., 2001). Beside these factors, a component in the construction should meet certain technical performance requirements to be considered reusable. In this section, different methods and approaches are discussed. Various studies have addressed the reusability assessment of different materials and components in construction. According to a recent review of circularity indicators in construction, reusability is one of the most commonly used key performance indicators (Khadim et al., 2022). Coenen et al., (2021) argued that reusability has three sub-indicators, disassemblability, transportability and uniqueness. The disassemblability and transportability are determined for the components and the uniqueness for the whole asset. Several digital technologies are utilized for assessing material reusability. Gordon et al. (2023) employed mobile photography and smartphone-based LiDAR devices for the recovery analysis of steel floor beams. Raghu et al. (2022) employed a deep learning approach alongside Google Street View in the building sector to identify reusable materials from buildings. This method effectively detects materials and elements and provides tailored reuse strategies based on their composition and construction year. Using street view images and computer vision techniques, Dai et al., (2024) assessed four exterior materials in the building stock of Merthyr Tydfil, Wales. This method enables the evaluation of potential material reuse at the component level._Akanbi et al., (2020) proposed a deep learning approach for forecasting reusable waste in the building sector. By matching different attributes of buildings (independent variables) and statistical data of demolition sector, they estimate the amount of reusable and recyclable materials prior to demolition. This method provides accurate results but relies heavily on a large dataset of previous renovation and demolition projects.

After reusability assessment, the next step is determining how and where the reclaimed material will be reused in another construction. This involves identifying the destination or receiving project and analyzing the financial, environmental, and other factors associated with the reuse process. In this stage of the circular renovation process, MFSA can be a useful tool for evaluating financial, environmental, and other factors related to the material reuse process. MFA is a well-established methodology for assessing sustainability in the built environment, and its application can be effectively extended to support circular economy practices (Pomponi and Moncaster, 2017).

In circular material flows, various cycles and reuse options are available. Identifying the appropriate reuse option for reclaimed materials depends on the specific objectives and constraints of a given project. It is crucial to explore all potential options. N. Zhang et al., (2021) developed a material flow model and argued that after deconstruction, materials can be reused in the construction phase such as system, components, part components or in the production phase; the latter is recycling as an input source for material production, but the former is material reusing in system level, refurbishing in component level or recycling for part component production. In some instances, materials may also be repurposed for entirely different uses. A huge portion of demolition waste is used as filler material for the construction roads (Di Maria et al., 2018). For concrete recycling, there are a few different reusing options. C. Zhang et al., (2018) examined four scenarios of recycling routes of concrete, 1) improving brick manufacturing, 2) recycling on-site for road base filling, 3) recycling aggregate for prefabricated concrete component and 4) recycling concrete aggregate for structure use. Chinda & Ammarapala, (2016) considered four reverse logistics method- direct reuse, recycling, remanufacturing and landfill- for decision making on construction and demolition waste management. They argued that two key factors-economic and site-specific- affect the decision making for reverse logistics plan.

2.2 Frameworks

López Ruiz et al. (2020) proposed a theoretical model for implementing CE strategies in the CDW sector. The model explores CE strategies that can be applied across five lifecycle stages: preconstruction, construction and renovation, collection and distribution, end-of-life, and material recovery and production. A framework developed by Sáez-de-Guinoa et al. (2022) incorporates circular economy strategies across different phases of the building life cycle, including design, manufacturing, construction, use, and end-of-life stages. De Silva et al. (2023) developed a framework to integrate circular economy principles into the renovation process. This framework includes circularity strategies that can be considered during various stages of the process. Fernandes & Ferrão, (2023) proposed a framework for circular refurbishment of construction. They argued that circularity strategies could be implemented during six stages of renovation process, including mapping, selective demolition, redesigning, production, construction and operation.

These frameworks offer valuable insights for incorporating circularity into the renovation process. However, they do not address multi-project contexts or the interactions between projects.

3 Multi-project approach

As discussed in the section 2.2, to date, most frameworks, focus on individual projects. This study proposes the renovation of a group of urban infrastructure projects undergoing renovation simultaneously. Figure **1** illustrates this new approach, representing a group of simultaneous projects {Project 1, Project 2, Project 3, …, Project n}. As shown different reuse cycles exist that indicated by arrows and varying colours to distinguish each cycle. Selecting the destination for reuse depends on the demand for the material and its quality. The reuse cycles are as below:

- Direct reuse within the same project and location. This applies when there is a demand for the material within the project, and its quality is considered suitable for reuse.

- Direct reuse in other simultaneous projects at another locations. This applies when there is demand for the material within the simultaneous projects, and its quality is considered suitable for reuse.
- Intermediate storage of materials allows for their direct reuse later. This is relevant when there is currently no demand for the material across any projects, and the quality of material is considered suitable for reuse. These materials will be reused when demand arises in one of the projects.
- Material repair, refurbishment, and remanufacturing are applicable when direct reuse is not feasible. The recovery method and the facility for processing (destination) may vary for each type of material. After recovery, these materials will be reused when demand arises in one of the projects.
- Repurposing materials for other demands in the same sector (construction) or other sectors.
- There is a flow of secondary material that may enter the material cycle. Originating from various sectors.

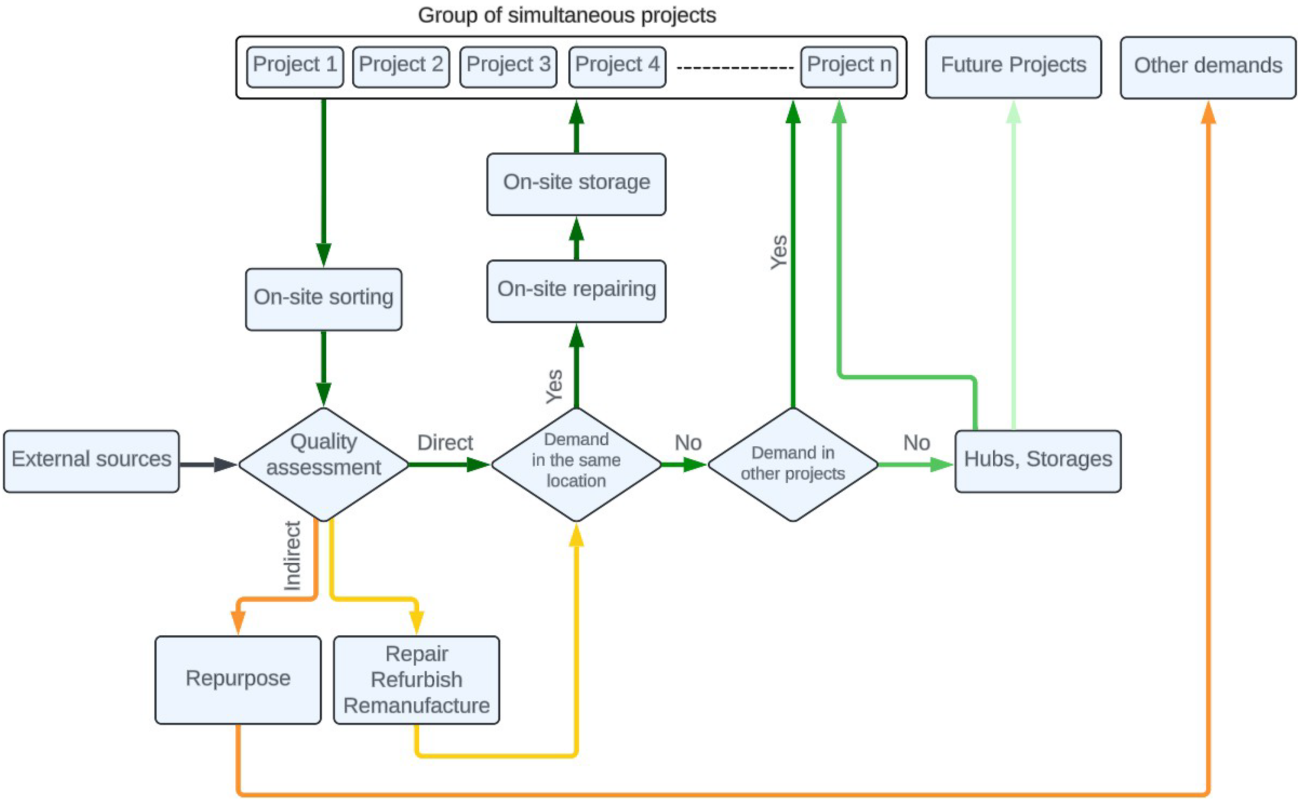

Figure 1 The multi-project approach (source: Created by authors)

4 Findings and Discussion

In the section 1 it is mentioned that in the urban infrastructure sector there are multiple projects under renovation concurrently. Therefore, in this study a new approach for construction renovation with a multi-project perspective is discussed. This multi-project approach offers several advantages compared to individual renovation projects:

- In this approach, the project donating the materials is aware of the receiving project, and vice versa. Essentially, the supply and demand for secondary materials are fully transparent to all stakeholders involved in the projects.

- When the supply and demand of secondary materials are identified, designers can incorporate them during the redesign stage, potentially enhancing circularity opportunities.

- In the construction industry, particularly in urban infrastructure such as bridges and quay walls, many components share a typical structure, with similar material types and dimensions. Consequently, adopting a multi-project approach for their renovation can significantly enhance circularity potential within this network of projects.

- In circular projects, collaboration between the project teams is crucial. In a multi-project approach, renovations are typically managed by familiar stakeholders who often share common interests and oversee multiple construction sites simultaneously. This arrangement facilitates site-to-site material reuse, increasing the likelihood of material sharing and ultimately enhancing the overall level of circularity across the projects.

- The integration of phases in the projects that have the role of donor and receiver in a circular system is important. The ideal integration of phases for reuse occurs when the reusability assessment of the donor structure is conducted before the conceptual design of the receiving structure. This phase integration is feasible when both the donor and receiver are identified during the planning stage. In a multi-project system, it is possible to plan beforehand, so the integration of projects could be optimal.

5 Conclusions and Further Research

In conclusion, this research developed a new approach for the renovation of urban infrastructure components in a multi-project context. The construction sector's significant contribution to global waste highlights the need for innovative methodologies. Infrastructure projects are *integral* to the urban environment and impact the entire city's residents, necessitating a different approach to their investigation. In the renovation of urban infrastructures like bridges and quay walls, where multiple projects occur simultaneously across the city, there is significant circular potential within this multi-project system. Within the developed approach at Figure 1, potential circular routes at the urban scale were identified. This new approach can provide new potential circular opportunities.

This research has the potential to enhance the overall circularity level of the renovation projects, offering broader sustainability benefits than isolated projects. This study can therefore contribute to the field of circularity in the urban infrastructure by developing a new approach for renovation of urban infrastructure. Nevertheless, this study has some limitations. These limitations could be addressed in future research as part of the next steps in the PhD journey. The reuse process discussed in the framework requires a comprehensive exploration of the financial, practical, organizational, environmental, and other associated impacts for each cycle. This calls for a multi-criteria analysis of different cycles within the framework, which will be addressed in future studies.

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