#249: A BIM-based framework for designing sustainable structures through the reuse of precast concrete components

Husam AL-JAWHAR[1], Georgia THERMOU [2], Carlos OSORIO-SANDOVAL[3], SERIK TOKBOLAT[4]

[1] University of Nottingham, University Park, Nottingham NG7 2RD, UK, husam-aljawhar@uobaghdad.edu.iq
[2] University of Nottingham, University Park, Nottingham NG7 2RD, UK, georgia.thermou@nottingham.ac.uk
[3] University of Nottingham, University Park, Nottingham NG7 2RD, UK, carlos.osorio@nottingham.ac.uk
[4] University of Nottingham, University Park, Nottingham NG7 2RD, UK, serik.tokbolat@nottingham.ac.uk

Abstract: The widespread use of concrete within the global construction sector is primarily attributed to its inherent qualities of resilience, versatility, longevity, and facilitation of economic growth. Nevertheless, it is noteworthy that this popular material is a significant contributor to the industry's greenhouse gas emissions, material depletion, and substantial waste production. Particularly in Europe, concrete constitutes the major component of demolition waste. Consequently, the practice of recycling and reemploying concrete components from pre-existing architectural structures harbours a considerable potential to attenuate the construction sector's ecological footprint substantially. This study presents a Building Information Modelling (BIM)-based reusability framework that aims to facilitate the reuse of precast concrete components in new sustainable structures, predicated on their performance and in line with specific matching criteria. This methodology involves utilising two distinct types of BIM models as input data. The first category, called 'Supply BIM', encapsulates data regarding existing components. In this category, the disassembly cost, the cost of each component, the disassembly durations, and the Life Cycle Analysis (LCA) of each component are calculated. Moreover, the load-bearing capacity of each component is analysed. The second category, termed 'Request' BIM, incorporates data necessary to reuse components during their subsequent lifecycle. The operational procedure relies on the BIM-based reusability model to aggregate matching concrete elements. Under the assumption that the Supply BIM possesses custom-built attributes equivalent to the Request BIM, the system will autonomously collect these components. This provides the foundation for a sustainable design for a new construction project. However, if the cost or LCA of the existing matching components exceeds that of the conventional new components, such components will be disregarded. This framework will underpin the development of a tool for designers that has the potential to reduce time and cost expenditures while minimising human error in sustainable design processes.

Keywords: Reusability Framework, BIM for Reusability, Circular Economy, Sustainable Structure, Precast Concrete Reuse.

1. INTRODUCTION

The construction sector represents a vital component of the economic structure and a significant contributor to the gross domestic product of any given country. This industry is implicated in the generation of over 35% of total waste and is accountable for approximately 5-12% of the total Green House Gas (GHG) emissions across Europe (European Commission Brussels, 2020). Further compounding this issue, the construction industry consumes approximately half of all non-renewable raw materials and accounts for 36% of worldwide final energy utilisation (Norouzi et al., 2021). Given these environmental considerations, there is an imperative to identify sustainable alternative materials. Reutilised concrete elements from existing structures present one such promising alternative to traditional raw materials. ISO 20887:2020 defined reusable as 'the ability of a material, product, component or system to be used in its original form more than once and maintain its value and functional qualities during recovery to accommodate reapplication for the same or any purpose' (BS EN ISO 20887:2020).

Crother (2005) and Salama (2017) mention that the typical design paradigm for building components does not incorporate considerations for disassembly, refurbishment, or re-utilisation. Nonetheless, the existing building stock presents substantial potential that can be tapped into, effectively diminishing reliance on novel designs and concurrently reducing both greenhouse gas emissions and the consumption of raw materials. This potential has drawn considerable attention from both researchers and industry practitioners, leading to an emphasis on developing methodologies to facilitate the re-utilisation of building components. Despite these advancements, the field is marked by a notable absence of a common understanding regarding the pertinent design principles for reutilised load-bearing structures, and furthermore, the prevailing design norms fall short in their support for such an approach (Akinade et al., 2020).

To overcome the inherent limitations of certain strategies, numerous studies have endeavoured to address these obstacles. Some have concentrated on the deconstruction of a structure, subsequently reconstructing the building in a different location (Van den Berg et al., 2021), while others have directed their attention towards the reuse of specific architectural components, such as concrete facades (Salama, 2019), neglecting the remaining structural elements including slabs, beams, and columns. It is essential to consider that various factors during the lifespan of a building, including but not limited to corrosion, load capacity exceedance, and other deteriorating conditions, can potentially alter or diminish the functionality of concrete. Unfortunately, existing research models overlook this significant detail, which could negatively impact the performance of new structures that incorporate previously used concrete elements and may even lead to instances of structural failure.

To address these deficiencies, the development of a novel framework is needed. This framework should be designed to facilitate the effective reuse of significant precast concrete components from existing structures, based on their performance. Such a model could be seen as a viable alternative to new construction, with the potential to bolster both sustainability and circular economy initiatives.

2. REUSABILITY OF CONCRETE COMPONENTS AND THEIR IMPACT ON THE ENVIRONMENT

In the United Kingdom, the construction industry stands as the most prominent consumer of materials and the leading producer of waste by volume. Data compiled by the Department for Environment, Food & Rural Affairs (Defra) indicated that 63% of England's total waste output, amounting to 120 million tonnes out of 189 million tonnes in 2016, was linked to the construction, demolition, and excavation sectors (GCB, 2020).

The production process of concrete significantly contributes to environmental pollution. Key ingredients such as limestone, chalk, clay, gypsum, and sand are subjected to heating at roughly 1450 degrees Celsius. Other components of concrete include water, cement, and aggregate, the procurement of which involves several environmentally impactful processes such as water harvesting, stone extraction, crushing for aggregate, and large-scale mixing. These materials are then processed into a fine powder known as cement (Stacey, 2011). Following this, the concrete components are transported from the extraction site to the production plant, where precise measurements are combined to yield cast-in-situ concrete. This is then transferred to construction sites or formed into precast elements. Each stage of this process, from resource extraction to demolition, is characterised by significant energy use and CO_2 emissions. The incorporation of clinker in concrete elevates the embodied energy and CO_2 emissions, with every ton of clinker produced resulting in one ton of CO_2 emissions (Cabeza et al., 2013).

Crowther (2005) proposed a critique of the prevailing "Cradle-to-Grave" life cycle model of building materials and components, which ultimately leads to substantial waste production. In contrast, the study advocated for a cyclical "Cradle-to-Cradle" model. If applied to the production and utilisation of concrete, this model could potentially not only conserve the energy required for material manufacture but also mitigate the associated CO_2 emissions, solid waste, and dust pollutants that arise from the demolition process, as depicted in Figure 1.

In a life cycle assessment conducted by Morrison Hershfield Engineering examining reclaimed precast double-T concrete, it was revealed that such usage could result in significant environmental savings (Catalli, 2009). According to the ATHENA Life Cycle Assessment, benefits included an energy savings of 1.23 GJ, a reduction in CO_2 emissions by 147 kg, and a 50% decrease in water and air emissions for each cubic meter of precast double-T concrete, as compared to using a new double-T (Catalli, 2009).

Further evidence of the utility and benefits of reclaimed concrete can be found in a housing project situated in Mehrow, near Berlin. This venture involved the reuse of precast concrete elements from obsolete buildings, originally built using the 'Plattenbau' construction technique, in the creation of new residences. The approach resulted in a noteworthy cost reduction of 30% (Stacey, 2011) (refer to Figure 2).

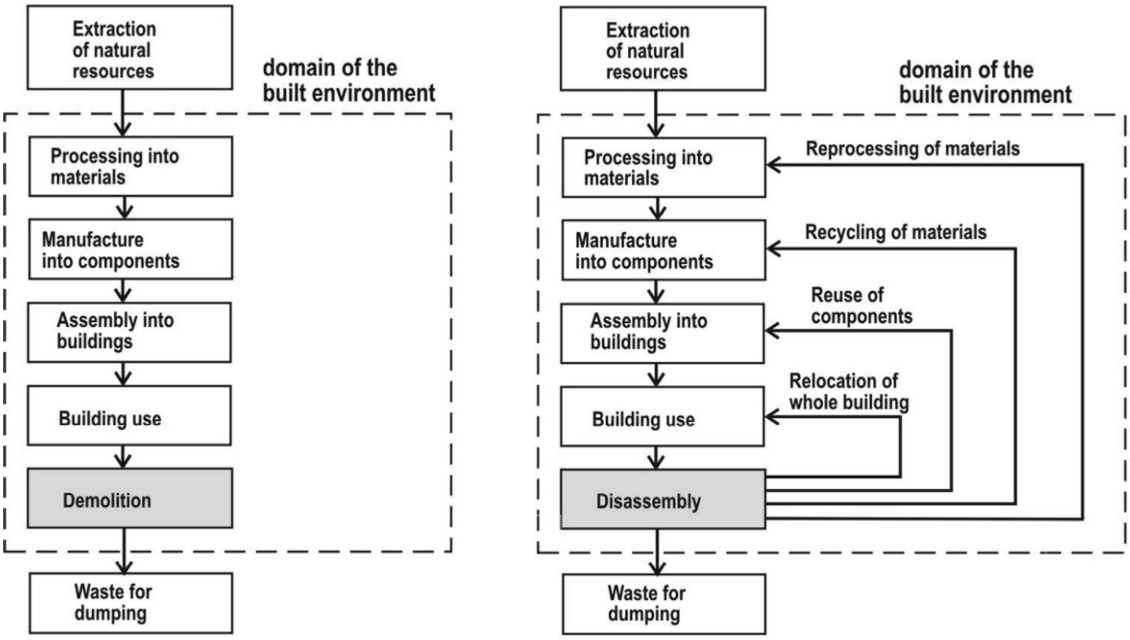

Figure 1 Changing the life cycle from linear to cyclic model through disassembly (source: Crowther, 2005)

Figure 2 Reuse of precast concrete slabs and panels for new housing construction in Mehrow, near Berlin (source: Stacey, 2011)

Moreover, a pragmatic study conducted by Piekko (2022) validated the economic and ecological viability of using reclaimed concrete in new construction. Their research demonstrated that new constructions using reclaimed concrete were less expensive and had a smaller environmental footprint compared to traditional construction methods (Table 1).

Table 1: Results of Demountable Three Different Construction (Source: Piekko, 2022)

Frame Type	Parts and Materials		Processes		New Building	
	Price (Euro)	Carbon footprint KgCo2	Price (Euro)	Carbon footprint KgCo2	Price (Euro)	Carbon footprint KgCo2
Conventional	8,754	5,712	0	0	8,754	5,712
Demountable "Wet"	8,908	5,734	2,235	15	98	179
Demountable "dry"	11,656	5,899	25	0	0	0
As a result, the total prices and carbon footprints are as follows:						
	Total Price (Euro)		Percentage %	Carbon footprint KgCo2		Percentage %
Conventional	17,508		100	11,424		100
Demountable "Wet"	11,241		64	5,928		52
Demountable "dry"	11,681		67	5,899		52

Components of concrete, such as beams, columns, and slabs, possess the potential for reuse, either for identical applications or for purposes that are similar. For instance, wall panels can be repurposed as fencing or noise barriers around highways proximate to residential zones, as well as walkways, platforms, and other landscaping elements. Concrete slabs could find renewed life as elevated flower beds, highway noise barriers, or fences, while beams and columns could be incorporated into landscapes and fences. Even suitable footings can be repurposed into structures such as retaining walls, dams, and water barriers (Salama, 2017).

Devenes et al. (2022) conducted an innovative study where they constructed a footbridge from 25 repurposed concrete blocks. These were interconnected through post-tensioning to generate a 10-metre span arch. The entire design and construction workflow of the prototype was documented, including sourcing of reusable concrete elements, structural design of the curve, and assembly. The non-destructive investigation, load testing, and Life-Cycle Assessment (LCA) were used to evaluate the mechanical properties and environmental impact of the Re: Crete arch prototype, Figure 3. Findings revealed that the reuse of concrete blocks yielded a structural behaviour analogous to an arch constructed from new or recycled concrete, yet it resulted in an environmental footprint that was more than 70% smaller.

Figure 3 Re:Crete footbridge prototype (source: Devenes et al., 2022)

There are currently few standards that acknowledge the deconstruction and subsequent reuse of structures. One such standard is ISO 20887:2020 (BS EN ISO 20887:2020), which defines reuse as the multiple uses of products or components without reprocessing for the same or different purposes. It excludes the preparation required for reuse, such as cleaning. A reused construction component should be functional in a different structure without the need for substantial repairs or modifications.

The principles of BS EN ISO 20887:2020 are applicable to assemblies and systems within a constructed asset, which can be deconstructed when the asset reaches the end of its lifespan or requires renovation. This allows for components to be repurposed. It is important to note that reusing older structures could be a significant strategy for addressing the current high carbon dioxide emissions and raw material consumption plaguing the construction industry. When construction components are deconstructed and reused, their total value, from both an economic and environmental perspective, is retained. Selling the same components multiple times effectively reduces their carbon footprint. Additionally, reusing these components decreases the need for virgin raw materials and new component production. For future reuse of new construction components to be possible, their connections must be designed for disassembly, in accordance with Design for Deconstruction principles.

Concrete, the predominant construction material, is responsible for significant waste and environmental impact (Crow, 2008). A growing global consensus has begun to view demolition as a design failure (Durmisevic, 2010). One prospective solution to mitigate concrete waste lies in the conceptualisation of buildings that can be easily disassembled, thus promoting reuse and adaptation (Salama, 2017). Although extensive research has been conducted in this field, there is yet to be a method that facilitates the reuse of specific concrete elements from existing buildings based on their condition and performance to construct new facilities according to the updated design requirements instead of using new raw materials. Thus, it is necessary to devise a comprehensive strategy that allows for the quantification of the benefits of adaptive building reuse via a computational method.

3. PRESENTATION OF THE PROPOSED METHODOLOGY

The proposed methodology utilises Building Information Modelling (BIM) environment to develop a framework for the reuse of precast concrete components in new, sustainable building construction. The main objective is to reclaim precast concrete components from existing buildings and prepare them for reuse in new construction, rather than disposing of them. To achieve this, a BIM framework is developed, and a computer-aided system will seamlessly integrate these reclaimed materials into the new construction project. The framework meticulously evaluates how well these elements align with the new requirements, highlighting the multitude of benefits associated with their reuse.

The challenges of the proposed research are:

1. Absence of previous research that focuses on reutilising individual structural elements and incorporating them into new buildings based on their performance. The bulk of prior research primarily investigates the possibility of reusing entire building components in different locations and functions or the potential for utilising specific portions of the existing building.
2. The lack of an effective automated method to ascertain which components of the existing building can be reused in the new building using a high-quality information model. Present studies often rely on the manual identification of features, which can result in delays, inflated costs, and inaccuracies.
3. Lack of information regarding the remaining structural integrity, physical degradation, or performance of reused components at the end of their life cycle or functional period.

3.1. Proposed Methodology

The primary function of this system is to evaluate the feasibility of reusing concrete components from existing pre-cast structures in new construction projects. The goal is to lessen dependence on fresh raw materials, enhancing environmental sustainability by reducing waste and lowering carbon emissions typically associated with new construction processes.

To achieve this, the system measures the performance of each precast concrete component, evaluating its current structural integrity and functionality. Factors such as durability, environmental resistance, and stability are considered. The objective is to determine whether the identified components can fulfil the functional requirements of a new design whilst maintaining their inherent performance characteristics.

The process that follows the identification stage involves creating a disassembly plan to assess the disassembly potential of each precast concrete component. This step necessitates an understanding of how a component can be safely removed from its current location without undermining its structural integrity. It is crucial to optimise the disassembly planning process, considering elements such as the type of bonding used, the component's design, and the potential impact of various disassembly techniques. Subsequently, operational costs, including disassembly, cost of components and the environmental impact of these operations, are calculated. All this information is then incorporated into the BIM system, known as the "Supply BIM," which serves as the initial input.

The design teams are then tasked with developing all the building details according to client requirements and needs. This information is entered into a secondary BIM, known as the "Request BIM," which serves as the second input.

To identify matching precast concrete components from the Supply BIM to the Request BIM, a matching function is utilised. This function facilitates the automatic reclaiming of substantial quantities based on size, performance, and other criteria. The Request BIM might require more than one Supply BIM, depending on the matching process. Therefore, this model is designed to minimise time, construction costs, and the expenses of examining the Supply and Request designs by each design team. It also mitigates potential human errors that may arise from manually investigating the cases for each building. Figure (4) illustrates the proposed framework, which comprises three modules as described in detail below:

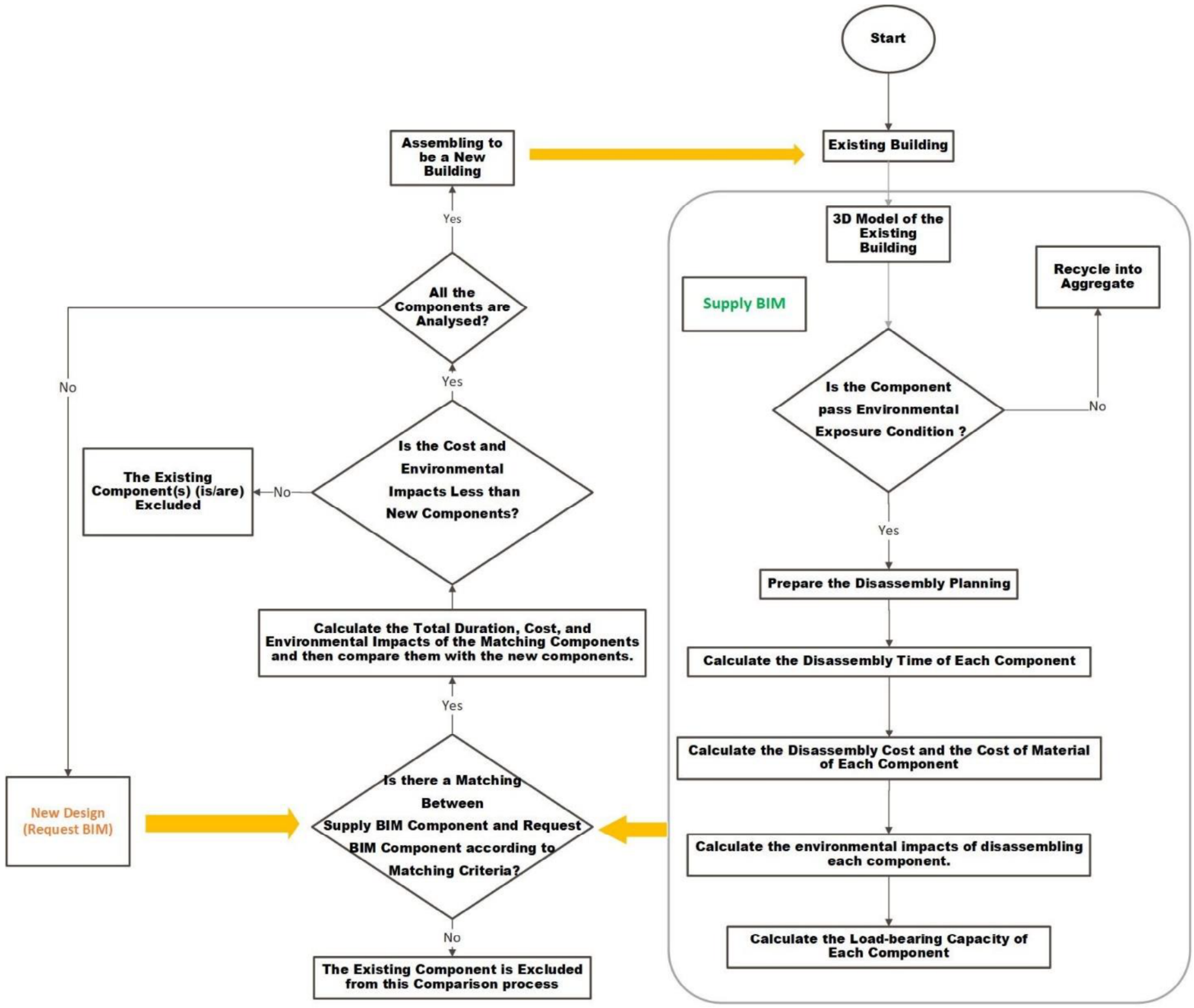

Figure 4 The Proposed BIM-based Reusability Framework

Module one; Supply BIM

This module aims to redefine the lifecycle of buildings, shifting it from the current linear model to a cyclic one, achieved through the reuse of concrete components. This approach aligns with the principles of a circular economy, contributing to more sustainable and efficient resource utilisation, which is increasingly becoming a necessity in the contemporary construction industry.

The initial stage of this proposed process involves inspecting each concrete component for its condition (e.g., corroded reinforcement, cracking) and structural capacity (e.g., flexural capacity). One method used in these inspections is Non-destructive testing (NDT). NDT techniques such as ultrasound, radiography, or ground-penetrating radar can provide valuable insights into the health of the components, detecting any latent defects or degradation without causing further harm to the components (Spears and Taheri, 2023). If the component meets the requisite criteria for structural integrity and safety, it is deemed suitable for reuse in another construction project. Conversely, components that fail to meet these standards must be responsibly discarded or repurposed.

The subsequent stage of this proposed process entails a detailed planning phase for the disassembly of the building. This step, one of great importance, necessitates a careful and systematic deconstruction process. The objective is to prevent unnecessary damage to the concrete components, requiring precision and attention to detail. Avoiding such damage is crucial, as it could potentially compromise the integrity of these components, causing them unsuitable for future reuse, a consideration of ultimate significance in our aim to promote sustainability. Thus, this phase demands a comprehensive understanding of the building's structural interrelationships, each playing its unique role in maintaining the stability of the structure. Furthermore, knowledge of component properties is important, as the characteristics of each type of component determine its suitability for reuse. Connection methods, too, need to be thoroughly understood, as their improper handling can lead to irrevocable damage. Overall, this process stage is a delicate balance of precision, knowledge, and execution, aiming to preserve the reusability of as many building components as possible.

The assessment and quantification of disassembly time in deconstruction processes are critical for optimising efficiency and resource allocation and for minimising disruptions. This consideration extends beyond the physical act of deconstruction to include the planning, coordination, and preparation phases, as well as contingencies. Accurate estimations of disassembly time are paramount to avoid increased costs and project delays. A comprehensive analysis of each component within the deconstruction operation can provide insights into the overall time requirements for the project. This enables better resource allocation and strategy development. For instance, understanding these time frames can aid in scheduling activities during off-peak hours to minimise disturbances in urban areas. The evaluation and quantification of disassembly time provide valuable data for decision-making in resource management and the development of disassembly strategies.

Following this often referred to as the cost component, a detailed and nuanced financial evaluation is carried out. This process essentially aims to quantify the economic implications of disassembling the building, including each individual component that constitutes the structure. In the study, each precast concrete component, such as slabs, beams, and columns, is identified, and the cost of each component is then estimated. The cost to disassemble each of these components is also calculated. These costs encompass various factors such as labour, the equipment needed for the disassembly, transportation of the salvaged material, and any potential repair or refurbishment costs required to make the reclaimed materials usable again. After the individual cost of each component has been estimated, these costs are then summed up to determine the total cost of disassembly. This provides an overall financial estimate of the disassembly process. This financial assessment serves a dual purpose. On one hand, it helps stakeholders understand the magnitude of the financial commitment required for the disassembly process. On the other hand, it provides a basis to evaluate the economic viability of this approach. A comparative analysis is then conducted between this approach and traditional methods of constructing new buildings. Material sourcing costs under conventional construction, which involve procuring new materials and their transportation, are compared with the costs of reusing reclaimed materials. This comparison offers a holistic view of the economic feasibility of the reclamation process. If the cost of disassembly and reuse is less than or comparable to traditional methods and offers benefits of sustainability or other strategic advantages, the reclamation process can be considered economically viable.

Life Cycle Assessment (LCA) is a systematic method used to assess the environmental impacts of a product, service, or system throughout its life cycle (ISO 14040:2006). In the context of the BIM framework, it's often considered the mainstay of its sustainability dimension. An LCA offers an in-depth analysis of the environmental pros and cons related to the execution of a proposed cyclic building lifecycle. This analysis involves examining all the stages of a building's life, from its inception, construction, use, and maintenance, to its end of life, including decommissioning, deconstruction, and eventual disposal or recycling (ISO 14040:2006). However, for the specific investigation described in this study, the LCA begins with the deconstruction phase of the building, which includes carefully dismantling the building to salvage components for reuse. The energy usage, greenhouse gas emissions, and other environmental impacts associated with this phase are meticulously accounted for in the LCA. The LCA continues with other phases of the building's life cycle, such as the processes involved in preparing the components for reuse, transportation of these components, and the environmental impacts associated with these processes. The final phase in this LCA is the reconstitution of the building's subsequent lifecycle. Here, the salvaged components from the deconstruction phase are used to construct a new building or to refurbish an existing one. The energy required for this phase, the emissions produced, and any potential environmental benefits derived from the reuse of materials are thoroughly analysed and recorded in the LCA. The ultimate goal of an LCA in this context is to provide insights into the environmental impacts of a building's life cycle. This information is instrumental in the design and construction processes, enabling architects, engineers, and other stakeholders to make informed decisions to reuse these components again or use new components that can minimise the environmental footprint of buildings.

Module two; Request BIM

In this stage of the process, the construction and design team engage in the critical task of translating the client's specifications into a coherent set of guidelines for the building construction. This phase is marked by a systematic approach that combines both established methods and significant considerations based on the unique aspects of each project.

The first step is to identify the needs and requirements of the client. This includes understanding the client's vision, goals, and practical needs for the building, taking into account factors such as the intended use of the building, target population, location, environmental conditions, budget, and timeframe. The team must gather, interpret, and confirm this information with the client to ensure alignment and prevent any miscommunication that could impact the project's success (Kamara et al., 2000).

Following this, the team embarks on the concept design stage. This is a creative phase where architects and designers formulate preliminary design solutions that fulfil the client's needs and requirements while adhering to regulatory constraints. The concept design usually involves creating sketches, drawings, and 3D models that visually represent the proposed building design. It is crucial at this point that the team effectively communicates these design ideas to the client for feedback and validation. Upon the completion of these stages, these detailed requirements are then integrated into the BIM system (Sarja, 2002).

The primary objective of this module is to act as a key input in the comparative analysis of BIM requests. This comparative process uses a variety of matching criteria to ensure accurate and useful comparisons. These criteria encompass a range of attributes, such as the geometric characteristics of the building design and its load-bearing capacity, along with a host of other factors that are crucial in architectural modelling and construction planning. Request BIM plays a pivotal role in supporting the main function of the system, details of which will be elaborated in the subsequent section. This ensures an integrated and comprehensive approach to BIM request evaluation and management.

Module Three; The main function

The third stage of this study involves identifying the desired functionality and architecture of a proposed method. Central to our proposed framework is the BIM-Based reusability concept.

To achieve this, two types of BIM are required: a 'Supply' BIM for existing buildings, which contains information relating to the existing precast concrete components, and a 'Request' BIM, which includes component reuse information for the second lifecycle (Yeoh et al., 2018). These were explained in the first and second modules, respectively. Components derived from the Supply BIM are incorporated into the process in a manner similar to those from the Request BIM. The process subsequently attempts to find a match between each existing component and the new design component based on specific matching criteria such as design life, load-bearing capacity, and geometry. If a component from the Request BIM satisfies all these criteria, it advances to the next stage.

At this stage, if both the cost and the environmental impact of the reused component are less than those of a new component, the process will select this component for assembly in the new building.

To develop this process, a sophisticated solution that harnesses the synergy of programming and technology is planned. Specifically, a computer-aided system using Autodesk Revit, a leading software in the architecture, engineering, and construction industry known for its BIM capabilities, is to be developed.

The deployment of Python, one of the most versatile and widely used programming languages, will be implemented in this endeavour. Python's extensive libraries and clear, readable syntax make it an ideal choice for such a project. With Python's integration into Revit, the automation of routine tasks, customisation of features, and innovation of new workflows are made possible.

By doing so, the efficiency, accuracy, and productivity of the work conducted within Revit are expected to be enhanced, thereby achieving the primary objective of this study.

4. CONCLUSION

Concrete serves as a pivotal element within the construction sector, albeit with substantial environmental impact due to the generation of considerable waste. Addressing this issue calls for the exploration of innovative alternatives to the employment of raw materials. A potential solution lies in the utilisation of pre-existing building structure components.

Indeed, existing models and methodologies are in place that promote the recycling of concrete through the demonstration of its utility in design for deconstruction. However, no existing frameworks propose the use of concrete elements derived from the existing building in alignment with fresh design necessities. If the performance of the structure has been altered, the question then arises: where should these components find new applications, and how can we systematically gather these elements without additional costs, time burdens, or errors?

This study aims to bridge these gaps, developing a framework based on BIM tools. With the creation of this framework, designers will be equipped with a tool that substantially contributes to sustainability goals. This approach curtails dependence on virgin materials, consequently reducing the environmental impact tied to the extraction and transportation of new materials. Furthermore, it prevents the unnecessary disposal of valuable materials into landfills, promoting their potential repurposing.

The Framework consists of two input data, the process, and the output. The first input is the details of end-of-service life buildings needed to transform into a resource for constructing a new building. For each component, three requirements are required to intuitively introduce the features' performance, identification, and disassembly sequence. a BIM model with these requirements is used that helps the existing disassemble buildings at the end of their life cycle or the function to provide the fundamental requirements for reusing again; this BIM will call (Supply BIM).

The result will be a BIM containing a portfolio, structure performance and information relating to the existing building components. The design teams should develop all the building details according to the requirements and client needs. All this information will enrol to another BIM called (Request BIM), which represents the second input. To collect the matching concrete parts from Supply BIM to the Request BIM, a BIM-Based framework that supports automatically reclaiming substantial amounts according to size, performance, and other requirements is used.

The proposed framework will be developed into a computer-aided program. It will serve as an integrative plug-in for BIM software within Revit, all of which will be facilitated through the versatile medium of Python. This framework's adoption promises not only environmental benefits but also significant time and cost efficiencies, lowering expenses and time commitments related to acquiring raw materials, equipment, labour, and more. It also optimises expenditure associated with landfill taxes and needless transport.

However, a common preference among clients leans towards the inclusion of new elements within their buildings. Hence, prior to employing this framework, designers must effectively communicate the advantages of this approach to clients, ensuring that the end result will align with the outcomes achievable using raw materials. Additionally, it is vital for the designer to verify that the buildings chosen for reuse are able to disassemble.

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