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Research Article

# From rubbles to digital material bank. A digital methodology for construction and demolition waste management in post-disaster areas

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## ABSTRACT

In 2020, European countries generated 807 mln tons of construction and demolition waste (CDW), accounting for 37.5% of total waste production. The UE Waste Framework Directive of 2008 established as a priority goal to increase the percentage of reuse, recycling and recovery of nonhazardous construction waste to a minimum of 70% by 2020. Pending the report that will define compliance with this goal, the average percentage currently stands at around 50%, of which only 3% involves upcycling operations. This doctoral research defines an operational methodology aimed at implementing digital processes for circularity in the AEC sector, with a focus on post-earthquake emergency Italian contexts. The treatment of CDW in earthquake-affected areas for the purpose of recovery/reuse, in a perspective of circularity, represents an underexplored field and limited, as in the rest of UE, to downcycling operations. By defining planning strategies and digital tools and procedures, the research aims to facilitate the reuse of building elements from post-earthquake demolition and reconstruction operations. The final output of the research consists of a cloud database, a Digital Material Bank (DMB), of informed building elements from post-earthquake selective demolition operations that can be reused in the construction market as a secondary raw material. The CDW management of the 2016 Central Italy earthquake is identified as the scope of application, with a focus on the situation in the Marche region. Finally, the main limitations and possible future scenarios of the research are reported.

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## INTRODUCTION

The term Industry 4.0 identifies the digitalization process affecting the economic sectors of contemporary society since the beginning of the 21st century. The objective of this model is to operate a complete integration of *IoT* (*Internet of things*) in these sectors. As reported by Chapman and Butry, the construction industry, or *AEC* (*Architecture, Engineering and Construction*), lags considerably behind others today [1], despite the environmental, economic and social impact this sector exerts globally.

According to the *Global Status Report for Buildings and Construction 2022,* the greenhouse gas emissions of the AEC industry reached the peak of 13.2 Gt in 2019. The global COVID-19-pandemic, and the subsequent decline in economic activity, reduced the AEC's emissions in 2020 (11.7 Gt). In 2021 we witnessed pre-pandemic levels being reached and exceeded, with a new peak of 13.6 Gt, 37% of

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global emissions[1] (Figure 1) [2]. The situation will presumably get worse for both the massive increase in investments (+51.9% in 2021 compared to 2015) and the growth in global population[2].

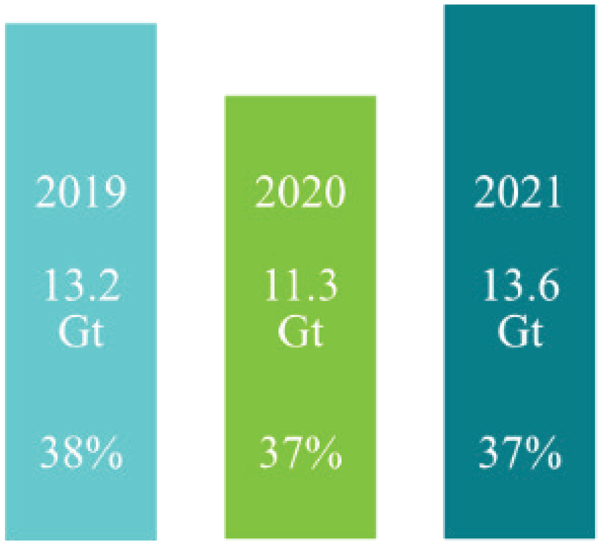


**Figure 1.** Greenhouse gas emissions from the AEC Industry (2019-2021).

The trend of waste production of the AEC industry, or *CDW* (*Construction and Demolition Waste*) is aligned with emissions. In 2020, Europe generated 807 mln tons of CDW, accounting for 37.5% of total waste production[3] [4]. In this regard, the *Waste Framework Directive* of 2008 established as a priority goal to increase the percentage of reuse, recycling and recovery of nonhazardous construction waste to a minimum of 70% by 2020[4] [5]. Pending the 2022 report, the average percentage currently stands at around 50%, mostly coming from downcycling applications, while only 3% for upcycling operations (Figure 2) [6].

While the overall construction waste average is in line with UE, the geomorphological features of the Italian territory aggravate the situation, behind one of the highest seismicity countries in Europe. To date, the production of demolition waste in earthquake-affected areas represents one of the main issues and challenges for Italy. Waste produced in such contexts generally belongs to two categories: waste from the demolition of unsafe and/or collapsed buildings, and provisional works dismantled at the end of safety operations. An estimated 497,486 tons of debris were removed in the province of Ascoli Piceno, following the earthquake of central Italy in 2016[5]. The treatment of this waste for the purpose of recovery/reuse, in a perspective of circularity, represents an underexplored field and limited, as in the rest of UE, to downcycling operations. On one

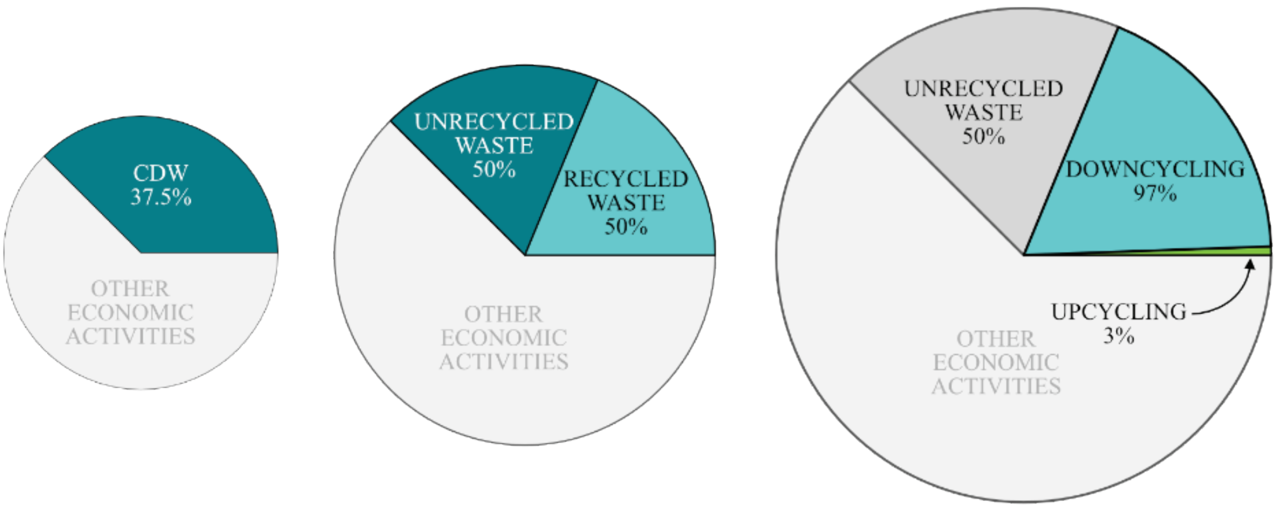


**Figure 2.** European CDW recycling statistics.

1 Data referred to the production and operational components.
2 The World Population Prospect 2022 estimates that the world population will reach 9.7 billion in 2050 [3].
3 Data extracted in January 2023.
4 The percentage is meant relative to the weight of the waste.
5 Data updated to 09/30/2021. Data refer to public rubble only. Public rubble is defined as "materials resulting from the partial or total collapse of public and private buildings caused by the seismic events, as well as materials resulting from the demolition activities of unsafe buildings ordered by the municipalities affected by the seismic events or other competent entities."

hand, in the Marche region, debris predominantly composed of aggregates (98%), once selected and crushed, has been transformed into recycled aggregates to be used for the construction of road sub-bases, embankments, etc. [7]. On the other hand, provisional works components, mainly of the wood type, have high circular potential, due to their homogeneous sections and absence of chemical treatment. The life cycle of these elements currently ends in landfills or as biomass, also involving the release of CO2 accumulated over time from the wood. Finally, to date there are no shared procedures, at the regulatory and operational level, aimed at the streamlining and efficiency of the recovery process, the reuse of this material directly in the post-earthquake reconstruction, and the definition of protocols capable of considering, from the design stages, the continuation of the life cycle of building components following selective demolition, with the consequent formation of new business models.

## DIGITALIZATION AS A STRATEGY FOR THE IMPLEMENTATION OF CIRCULAR PROCESSES

In this scenario, the digitalization of the AEC industry, especially in the emergency context, assumes a crucial role. The urgency to adopt responsible strategies for the design, production and management of the built environment leads to considering *data* as the raw material underlying the entire supply chain. The collection and management of data makes it possible to read and interpret the criticalities of building processes throughout the entire life cycle of architectural artifacts, and to implement multi-criteria optimization strategies. It is no coincidence that technological developments in the AEC industry, during the 4th industrial revolution, have been primarily concerned with data, addressed in the nuances of design, production and management of the built environment.

The main novelty in the design field is represented by an approach involving the extension of human capabilities through the use of computers, defining a new design philosophy known as *procedural design* (PD) [8]. The main difference, compared to traditional design, is the development of a set of rules and processes that produce a geometric and/or informational output from the transformation and management of data [9]. Through PD, designers are able to deal dynamically with data complexity, made manageable through the use of algorithms, in a precise and efficient manner.

In the field of building management, numerous tools have been developed that fall under the label of *Building Information Modeling* (*BIM*). The term stands for the "*use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions*" [10]. The BIM methodology was born in response to the problem of the *MacLeamy curve* (Figure 3) within the construction history: moving forward in the life cycle of a building artifact, the impact of new choices on the project decreases, while the costs associated with those choices increase. The BIM methodology operates a shift of effort in the design phases, where choices determine a strong impact on the project while minimizing costs. Through a digital simulation of the building process, potential issues are anticipated as early as the design and pre-design phase [11].

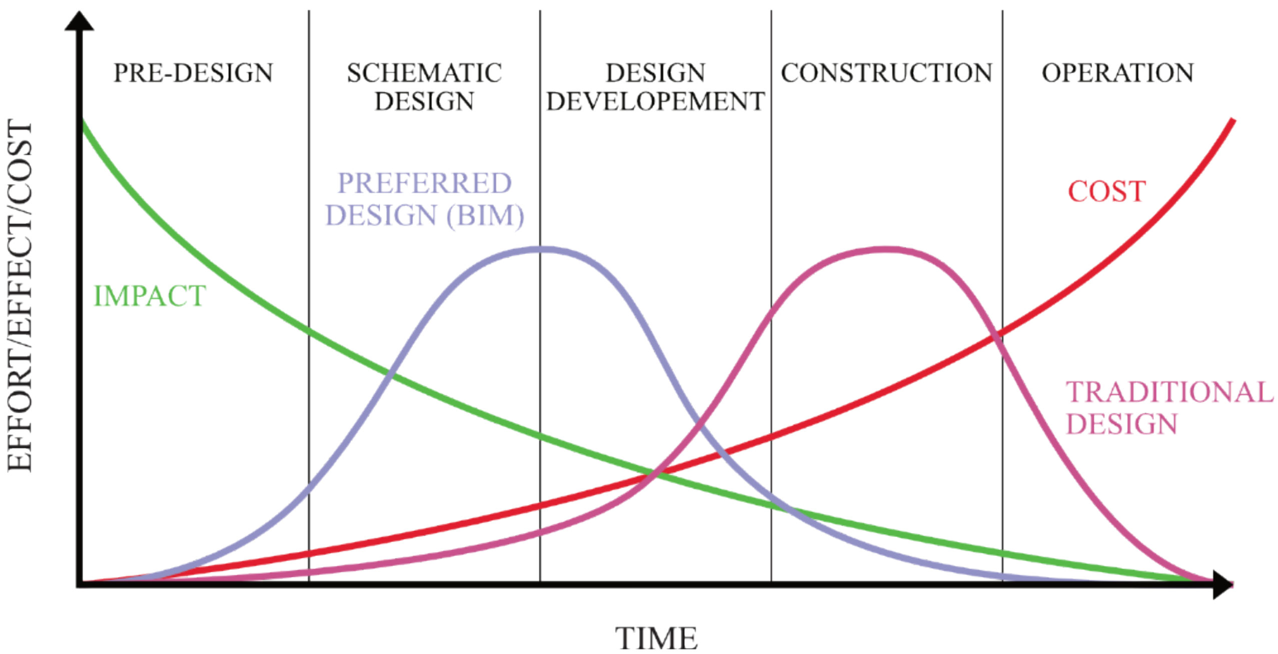


**Figure 3.** MacLeamy curve adapted to BIM.

The BIM methodology has many advantages in terms of economic and environmental sustainability, but it is currently marked by theoretical and practical limitations. BIM appears to be applicable mainly to new buildings, demonstrating significant shortcomings toward existing artifacts, especially historical ones. The geometric representation of such artifacts is not easy, thus also limiting the information potential of the building system. Despite efforts toward so-called *openBIM*[6], such tools are also unable to guarantee a constant information flow in the exchange of data between software. This shortcoming leads to disruptions in operational workflows, reducing the effectiveness of the goals set by the BIM methodology. In addition to issues related to computer tools, which are currently limited to extremely sectoral stages, the absence of a unified, shared, and comprehensive methodology poses a main limitation.

Such a described cultural context thus creates significant difficulties for designers and stakeholders when attempting to address the sensitive issue of circularity in relation to the digitalization processes in the AEC industry.

## RESEARCH OBJECTIVES AND PHASES

The current research of the authors, carried out at School of Architecture and Design of the University of Camerino (Italy), define an operational methodology aimed at implementing digital processes for circularity in the AEC sector, with a focus on post-earthquake emergency contexts. The research focus is on the sustainability implications of the formation of a new market that can attract opportunities and investments. By defining planning strategies and digital tools and procedures, the research aims to facilitate the reuse of building elements from post-earthquake demolition and reconstruction operations. For provisional works, the research provides the integration of such procedures as early as the immediate post-installation phase. The research also aims to provide alternative solutions for both streamlining upcycling procedures for construction waste and facilitating post-earthquake reconstruction operations through a concrete economic boost. Constant discussion with administrations, local authorities and economic actors are key factors to immerse the research within the dynamics that characterize the AEC sector. The use of IT tools is conducted following the perspective of interoperability and responsiveness, in order to limit the loss of data during the various stages of research, optimizing the workflow in terms of timing and accuracy of operations. The final output of the research consists of a cloud database, a *digital material bank* (*DMB*), of informed building elements from post-earthquake selective demolition operations that can be reused in the construction market as a secondary raw material, while defining strategies to facilitate new business models. The research mainly involves three phases:

- state of the art analysis and market surveys;
- development of methodology;
- pilot design application

### Analysis and market surveys

The first step of the research involves a market survey, with a focus on the Italian and regional AEC industry in the post-earthquake context. The survey aims at understanding the potential and interest that digitalization processes for circularity exert, and will exert, within the construction supply chain. This phase consists of collecting a large amount of data in order to accurately describe the current and projected situation of the circularity market in the AEC sector. The dialogue with stakeholders (local authorities, companies, economic actors) is pivotal to analyze the opportunities, benefits, and large-scale applicability of circularity processes. In addition, the research analyzes the current legislative and administrative apparatus to assess the level of depth and criticality of circularity processes within the post-earthquake demolition and reconstruction scenario. Moreover, the research addresses the application and management limitations currently found in digitalization processes. These limitations include IT issues (software and hardware), interoperability, cloud data, traceability, certifications, etc. This first phase takes place with parallel insights regarding the topic of circularity in AEC, with a focus on international academic developments and applications conducted on the built environment.

### Methodological development

#### *Data acquisition*

The first task of the methodological development is the identification of strategies for acquiring the information of the building elements, from the post-earthquake demolition operations, that make up the DMB. The data to be acquired are: the identity of the building elements, geometry, typology, materials, weight, chemical and physical characteristics, architectural and geographical location (to be integrated with *GIS* systems), and information related to the production, installation, and management of the elements. The retrieval of such information is also addressed through analysis of data from existing databases using programming tools. Related to geometric surveying, the topic of photogrammetry (*Structure from Motion*) is integrated in the workflow, including the subsequent processing and management of point clouds using algorithmic support for classification, segmentation, etc.

6 "openBIM extends the benefits of BIM (Building Information Modeling) by improving the accessibility, usability, management and sustainability of digital data in the built asset industry. At its core, openBIM is a collaborative process that is vendor-neutral. openBIM processes can be defined as sharable project information that supports seamless collaboration for all project participants. openBIM facilitates interoperability to benefit projects and assets throughout their lifecycle." [12]

***Building elements analysis***

Once the data are collected, the building elements are subjected to analysis to understand their state of preservation (Figure 4). The analyses cover the mechanical strength of the elements, the state of deformation, the presence of aesthetic imperfections and deteriorating conditions, etc. The analyses are conducted in an automated manner using *VPL* (*Visual Programming Language*) computational tools. The analyses aim at defining the economic value of the objects, as well as understanding the degree and contexts of reusability.

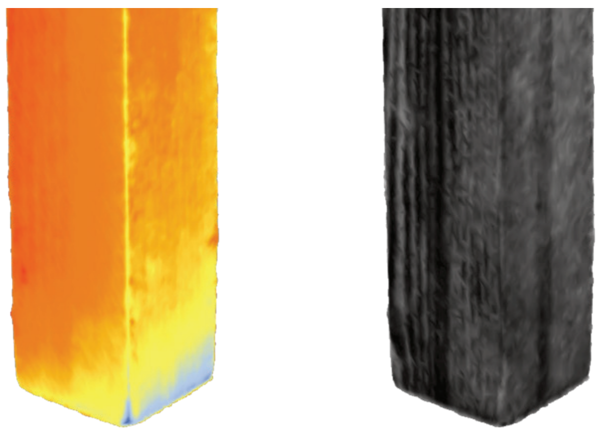

**Figure 4.** Analysis detail of a building element for deformation (left) and texture quality (right).

***BIM* compiling**

The collected geometric and descriptive data need to be represented within platforms capable of synthesizing and organizing the different categories of information. BIM tools are be used for this phase, developing procedures to automate the compilation of information and the conversion of meshes, obtained from 3D scans, into *Brep* (*Boundary Representation*), the native geometric typology of the main BIM software. Connection tools between BIM and VPL tools are used. The outcome of this phase is a *digital twin*, i.e. a digital alter ego of the database of real elements (Figure 5).

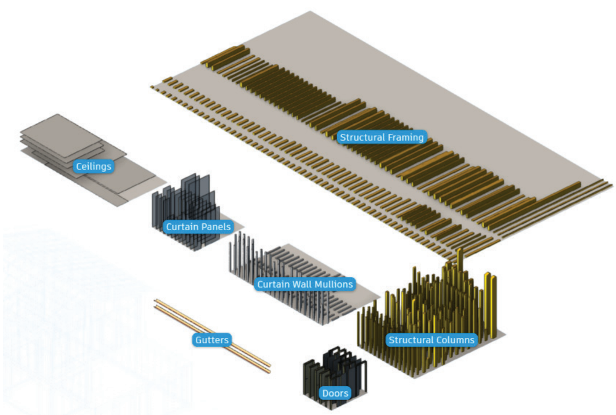


**Figure 5.** Digital twin of the building elements.

***Life cycle assessment***

Within the circularity dynamics for the AEC sector, *life cycle assessment* (LCA)[7], plays a key role in simulating their environmental footprint, in terms of CO2 equivalent, from the extraction of the raw materials to the decommissioning and/or reuse. The goal of this phase is to develop decision-making strategies to optimize the use of building elements in the AEC industry for a responsible and sustainable design approach. This operation contributes to the creation of comparative models between conventional and circular practices.

***Dashboard and reports***

The data collected and processed in the previous phases need refinement aimed at making such data readable and interpretable in a clear and effective manner. Therefore, strategies are developed, both on the IT and communication level, for producing interactive reports and dashboards (Figure 6). A high degree of interoperability among the tools

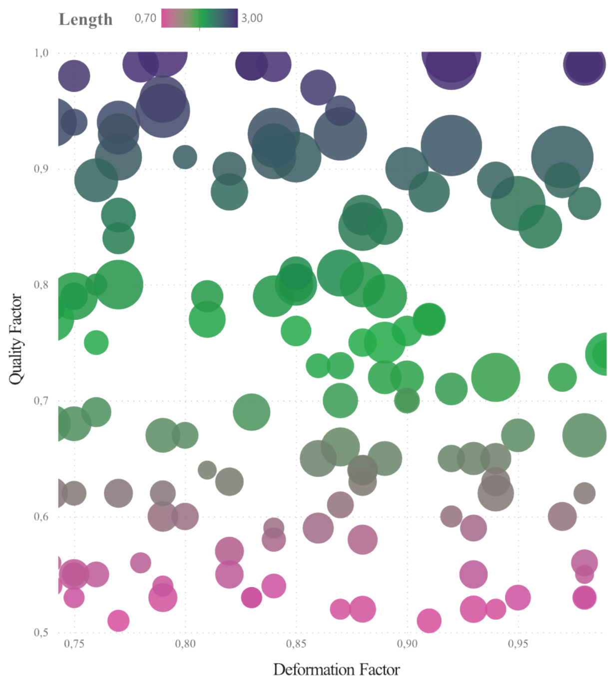


**Figure 6.** Interactive dashboard of the digital material bank.

7 LCA is defined as "a technique for assessing the environmental aspects and potential impacts associated with a product." [13].

involved is maintained in this phase as well, so any kind of updates from previous phases will be responsively reflected in the reports. The outcome of this phase composes an initial finished and autonomous product, which can also be summarized by means of technical data sheets and certifications, to be submitted to the attention of the stakeholders to obtain feedback about possible investment interests.

***Cloud database***

The next step of the research is the *cloud* publication of the DMB generated in the previous steps. The main challenge is the programming of a bidirectionally interactive database, so that any changes can be updated simultaneously on both the digital twins and the cloud database itself. Strategies are planned to track updates and to manage the usability, accountability, and security levels of the database.

***Worksites***

The operations described so far involve an initial transition from the physical to the digital world, converting building elements into a condensed dataset within a fully digitized database. The next step is to return research within the physical world in order to develop strategies that can be traced back to the worksite domain. These include the use of *RFID* (*Radio Frequency Identification*) technologies and *QR codes* that can be physically applied to the building elements of the database, also with the support of augmented and virtual reality technologies, in order to visualize and edit the data associated with the elements.

***Design applications***

As a conclusion of the research, it is proposed to verify the applicability of the system by carrying out a pilot architectural project. The design of the pavilion will be done by taking into consideration only the database building elements, which can be considered as secondary raw material, from the post-earthquake selective demolition operations. The design will be addressed with the aim of *loop algorithms* which operate successive iterations to select from the database, for each design architectural element, the most suitable building element for design purposes. The architectural product will again trigger circular procedures: its component building elements will re-enter the database with updated information to be reused in the future.

***Comparative models***

Finally, comparative models between traditional and circular approach are conducted to highlight the benefits of the latter in terms of environmental impact, economic savings, waste generation and opportunities for local governments and businesses.

The research is currently in the first of three planned years of the Ph.D. program in Architecture, Design and Planning at the International School of Advanced Studies of the Camerino University, curriculum in Innovation Design - Design for environmental sustainability and for process and product innovation. In addition, a baseline trial of the entire process of digitizing construction waste was initiated in order to understand the constraints, requirements, objectives and data crucial for methodological development. Future research developments will involve theoretical and practical insights into the individual steps of the methodology, which will be interspersed with milestones that can be configured as stand-alone products.

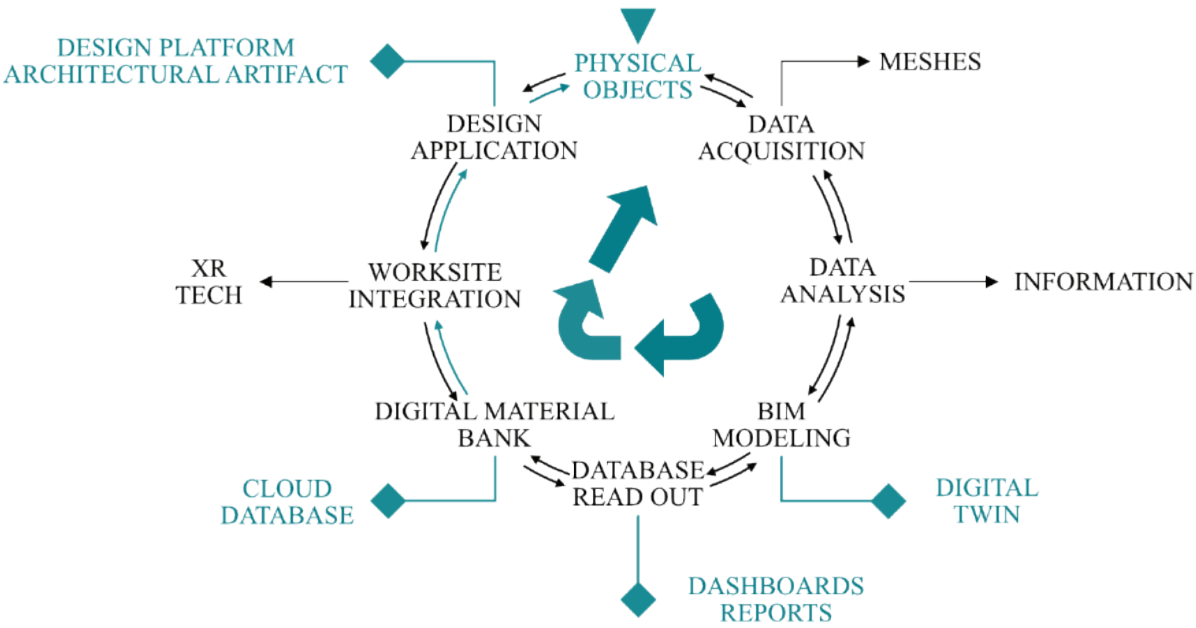


**Figure 7.** Methodology summary diagram.

## FIELD OF APPLICATION AND EXPECTED OUTCOMES

Demolition and reconstruction operations after the 2016 Central Italy earthquake is identified as the scope of application, with a focus on the situation in the Marche region. The proposed methodology provides numerous advantages for local governments and companies operating in the AEC industry, as well as benefits in terms of environmental sustainability. The research provides a system for the upcycling of construction and demolition waste and in which the elements to be used for provisional works are produced, processed, certified, and installed following certain planned procedures in such a way that they are considered, from the earliest stages of their life cycle, as elements that can potentially be reused in the future as secondary raw material. It would thus open up the possibility for companies to purchase materials in advance at a subsidized price since they are reusable only after dismantling. In addition, such a system is convenient for local governments as they would be able to benefit from economic subsidies that can be reused directly in safety and post-earthquake reconstruction works. Finally, the reuse of such building material leads to a significant reduction in waste production and greenhouse gas emissions. However, the proposed methodology is applicable in a variety of contexts, not necessarily emergencies, and to the entire caseload of technological units and building materials.

The main limitations of the research relate to the difficulties of incorporating this methodology within the European and national regulatory framework. A reform in this sense is auspicable in order to fulfill the paradigms of Architecture 4.0 for circularity processes in the construction sector, not only for new construction. From an IT point of view, the geometric and informational representation of certain categories of building elements (e.g. aggregates) remains uncertain to date. In addition, tools for converting point clouds, derived from photogrammetric surveys, into BIM objects need further development to ensure a high level of automation of the process itself. Possible future scenarios for the advancement of the research project involve the integration of artificial intelligence within the process. The use of AI and Computer Vision can potentially automate the entire process of acquiring the different layers of information (geometric, material, presence of degradation). Such acquisition represents today the most time-consuming and complex operation in terms of accuracy. Thus, AI contribution could be a winning strategy to augment design and management capabilities in the construction industry, within the circularity framework.

## CONFLICT OF INTEREST

The authors declare no potential conflicts of interest regarding the research, authorship and/or publication of this article.

## DATA AVAILABILITY

The data used to support the findings of this study are included within the article.

## AUTHOR’S CONTRIBUTIONS

All authors are contributed equally to bring out this article.

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## REFERENCES

[1] R. E. Chapman, and D. T. Butry. “Measuring and improving the productivity of the U.S. construction industry: Issues, challenges, and opportunities,” National Institute of Standards and Technology, Gaithersburg, Master Thesis, 2008.
[2] United Nations Environment Programme, “2022 Global Status Report for Buildings and Construction: Towards a Zero emission, Efficient and Resilient Buildings and Construction Sector,” Nairobi, Kenya, 2022.
[3] United Nations Department of Economic and Social Affairs, “World Population Prospect 2022: Summary of Results,” United Nations Publication, New York, NY. 2022.
[4] Eurostat, “Waste Statistics”, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics Accessed on Apr 18, 2023
[5] European Union, “Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives”, Official Journal of the European Union, Strasbourg, France. 2008.
[6] Interreg NEW, “Digital deconstruction - advanced digital solutions supporting reuse and high-quality recycling of building materials,” https://www.nweurope.eu/projects/project-search/digital-deconstruction/#tab-1 Accessed on Apr 18, 2023
[7] G. Marchetti, and P. Ranzuglia, “Gestione delle ‘macerie’ nell’ottica dell’economia circolare. Le caratteristiche degli aggregati riciclati prodotti nel cratere del sisma 2016,” Ecomondo, 2021
[8] D. Stasiuk, “Design modeling terminology,” https://archinate.files.wordpress.com/2018/06/dstasiuk-design-modeling-terminology1.pdf Accessed on Apr 18, 2023
[9] A. Tedeschi, “AAD - Algorithms-Aided Design. Parametric Strategies using Grasshopper®”, Le Penseur, Brienza, 2014

[10] International Organization for Standardization, “Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles (ISO Standard No. 19650-1:2018),” 2018 https://www.iso.org/standard/68078.html Accessed on Apr 18, 2023

[11] A. Ferrara, and E. Feligioni, “BIM e Project Management. Guida pratica alla progettazione integrata,” Dario Flaccovio Editore, Palermo, 2016.

[12] buildingSMART International, “openBIM,” https://www.buildingsmart.org/about/openbim/ Accessed on Apr 18, 2023

[13] International Organization for Standardization, “Environmental management - Life cycle assessment - Principles and framework (ISO Standard No. 14040:2006)”, 2006. https://www.iso.org/standard/37456.html Accessed on Apr 18, 2023.