Framework for a Multi-level Approach for Testing the Construction Demolition Waste Hierarchy

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Abstract. The Waste Framework Directive (WFD) proposes a Waste Hierarchy (WH), a list of waste management strategies ordered from the most to the least preferable and often illustrated as an inverted pyramid. Waste prevention is at the top of this pyramid, followed by preparing for reuse, recycling, and then other recovery activities such as waste to energy. At the bottom of this hierarchy, the waste management strategy to be avoided is waste disposal at landfills.

Although this hierarchy establishes a logical framework for waste management policies, case-by-case assessment shows many exceptions to the rules implicit in this structure. Indeed, depending on the materials and constructive solutions, the order proposed by the WFD can be modified by considering a detailed LCA. On the other hand, when performed on an element level, the results of LCA may not be viable to inform policymakers on the best course of action towards a more sustainable built environment. This paper proposes a multi-level approach – at a material, element and building level – combining the waste hierarchy with the 9R framework. Assessments of building refurbishment at the building or element level can yield vastly different results, which may be relevant when addressing questions posed by each type of stakeholder according to their scope of action.

Keywords: Construction and Demolition Waste Management · Construction · Life Cycle Assessment (LCA) · Refurbishment and Maintenance · Waste Hierarchy (WH) · 9R Framework

1 Introduction

A circular economy (CE) is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times [1]. A CE approach helps to reduce environmental degradation and fosters resource efficiency. Ultimately, it minimises waste generation, thus enhancing sustainability [2]. Sustainability assessment is a field in continuous evolution in which the legal framework is crucial to push the adoption of sustainable principles. However, it is important to note that there is a disparity between legislation evolution and the ongoing scientific development and

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methodological approaches. This paper proposes a combination between the 9R framework (9R) [3] as a frequently used hierarchy and the Waste Hierarchy (WH), proposed by the Waste Framework Direct (WFD) [4], and its adaptation to the construction sector. Additionally, a framework is explored to guide various stakeholders' decisions, using an approach focusing on the end-of-life (EoL) phase and based on currently available LCA data. A more comprehensive LCA approach is difficult to achieve due to the complexity of LCA studies and lack of research focusing on alternative EoL scenarios. This work responds to the research gap in the application of the WH and 9R to the construction sector by introducing a framework to guide decisions for refurbishment and maintenance purposes.

2 Literature Review

2.1 The Waste Hierarchy

The WFD [4] was initially published in 1975 and was revised in 1991, with the most recent version published in 2008. Since then, several authors proposed adaptations tailored to specific sectors, such as the Delft Ladder (2000) developed for application in the construction sector. This ladder recommends that, for optimal construction practices, the use of "*hard-to-recycle materials*" should be minimised and the separation of materials and building elements enhanced, stating that constructions should be designed for easy disassembly [5].

Table 1 contains the definitions of recycling and reuse from different sources, highlighting similitudes and differences among proposed definitions. The definitions in most of the documents presented [6–9] are in accordance with the WFD [4], however, the other documents define reuse acknowledging different purposes than the one for which it was initially conceived [10, 11]. The WFD was amended in 2018, but the definitions remain unaltered, and '*reuse*' only encompasses the cases in which the product/component serves the same purpose for which they were conceived. The WFD also defines '*preparing for reuse*' differentiating it from '*reuse*'. In the context of '*reuse*', the material or object has not yet become waste. On the other hand, in the case of '*preparing for reuse*', the material has already been designated as waste, and to be declassified as waste, specific actions such as checking, cleaning, or repairing are needed. These recovery operations ensure that products or components are prepared for reuse without requiring any additional pre-processing. The Ellen MacArthur Foundation definition of '*reuse*' [12], which intends an international scope, seems to be partially in accordance with the WFD but seems to include '*preparing for reuse*'. Other definitions, such as repair, need to be further detailed in the waste hierarchy.

Several concerns within the WH were pointed out in the literature, such as: *"not distinguishing between different forms of recycling"* and even though it presents a *"solid strategy for avoiding landfill, there is doubt about the merits of the hierarchy concerning minimising environmental impacts and natural resource use*". Some of these issues can be overcome by providing stricter guidance on WH implementation [13].

Table 1. Review and comparison of reuse and recycling definitions.

[Year] Reference	Reuse definition	Recycling definition
[2008] Directive 2008/98/EC 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) [4]	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations
[2016] Protocolo de Gestão de Resíduos de Construção e Demolição da EU [6]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2018] Guidelines for the waste audits before demolition and renovation works of buildings [10]	Using materials or building elements on more than one occasion, either for the same or for a different purpose, without the need for reprocessing	A process where materials are collected, processed and re-manufactured into new products or use as a raw material substitute
[2020] CE Principles for Building Design (EU) [7]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2020] ISO 20887:2020 Sustainability in buildings and civil engineering works [11]	Use of products or components more than once for the same or other purposes without reprocessing	Ability of component parts, materials or both to be separated and reprocessed from products and systems and subsequently used as material input for the same or different use or function*
[2020] Regime Geral de Gestão de Resíduos (RGGR) [8]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]

(*continued*)

Table 1. (*continued*)

[Year] Reference	Reuse definition	Recycling definition
[2021] Framework Level(S) [9]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2021] Ellen MacArthur Foundation Glossary [12]	The repeated use of a product or component for its intended purpose without significant modification. Small adjustments and cleaning of the component or product may be necessary to prepare for the next use	Transform a product or component into its basic materials or substances and reprocess them into new materials**. Embedded energy and value are lost in the process. In a circular economy, recycling is the last resort action

*definition of recyclability
** definition of recycle

2.2 The 9R Framework

Parallelly to the WH, the 9R proposed by Potting also defines one hierarchy to reduce environmental impacts and boost the circular economy from the most preferable approach: refuse; to the least preferable one: recover [14].

Previously to the 9R framework, a wide variety of n-R approaches was found in literature varying not only the numbers of Rs (3Rs, 4Rs or 6Rs), but also assigning different attributes and meanings to each R. Notably, the number of Rs tends to increase in recent contributions, published after 2010 [15].

Potting recognises exceptions for his framework and advises that the examination of rebound or secondary effects is advisable, but, in general, increased circularity in a product chain results in reduced consumption of natural resources and materials. This, in turn, leads to fewer environmental effects within that product chain and related chains. Although the hierarchy ranks the most to the least favourable strategy, there is still a great need to consider the best solution approach applicable to each case within each specific context [16].

2.3 Life Cycle Assessment Approach

LCA studies are one methodological approach to assess the impacts associated with each activity, product, or material. LCA studies should have a holistic approach, focusing on all the stages of the life cycle of a product, including the EoL. Therefore, LCA could be used to determine the best course EoL strategy, if not for their complexity and time-consuming nature [13].

Neither of the hierarchies that were previously presented, WH and 9R, consider the different characteristics of the different materials. For example, steel structures with demountable connections and prefabricated assemblies comprise mostly reusable materials, while concrete structures may generate recyclable materials [17]. Because different materials require different EoL strategies, sorting is considered a preliminary and essential step before the appropriate waste treatment [18]. Separation allows for action on a smaller level, allowing the preparation for reuse to reduce material consumption or adopting a more appropriate EoL strategy based on the specific material.

LCA studies results, focusing on EoL strategies, would be an important data source but, unfortunately, are hard to compare for various reasons: i) lack of transparency in the definition of the system boundary, ii) uncertainty about life cycle inventory (LCI) data origin; or iii) sensitivity analysis of the assumptions made [19, 20]. Adding to this complexity, different locations have differences in climate, energy mix or the local market available, meaning the same product will have incomparable results [21].

The paper aims to combine the two hierarchies, WH and 9R, adapt them to the construction sector, and create a guideline to help stakeholders choose the preferable EoL strategy.

3 Methodology

3.1 Combination of the 9R Framework and Waste Hierarchy

As previously stated, the WH's main goal is the generation of less waste, not necessarily the minimisation of environmental impacts. As for the 9R, it presents exceptions in the form of rebound or secondary effects. The main proposition of this paper is the association of the two frameworks, as presented in the WH and 9R [3, 22–24], Fig. 1, and their application to the construction sector, presenting some practical examples in Table 2.

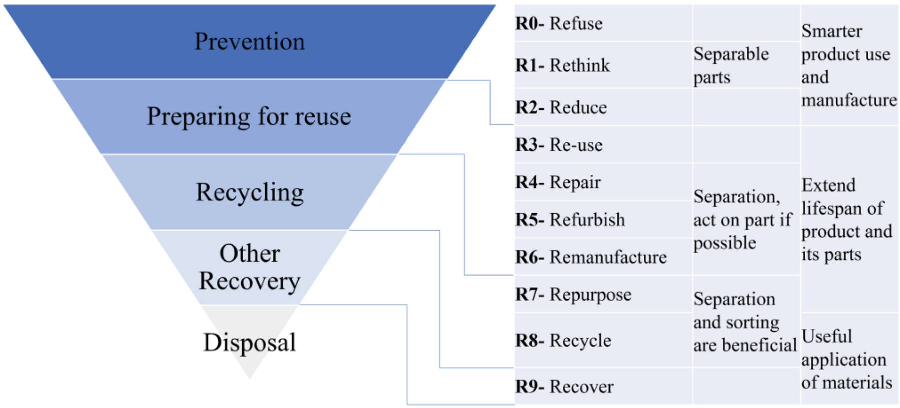

Fig. 1. The WH and 9R [3, 22–24].

Table 2. The 9R Framework, definitions, and examples.

9R	Definition	Example in construction	CE approach
R0-Refuse	Avoid both virgin and processed materials, no action	Acceptance of damage (e.g., the darkening of a natural stone with no substitution needed)	Smarter product use and manufacture
R1-Rethink	Design or redesign a product or component based on sustainability and circularity principles, choosing a more sustainable option, Solving with minimal resources	Design for disassembly (e.g., Modular construction, demountable building elements)	
R2-Reduce	Reduce the use of raw and processed virgin materials, increase efficiency, and choose the most sustainable option	More precise design and construction (e.g., BIM use of clash detection)	
R3-Reuse	Reusing products, components, or virgin materials (whether they have previously been refurbished), preferably reusing in the same place, avoiding transportation	Reuse elements from previous construction (e.g., use of a marketplace. Note: If possible, avoid transportation)	Extend the lifespan of the product and its parts
R4-Repair	Regular maintenance and repair, whether (or not) combined with redesign and digitalisation. Minor adjustments, minimal intervention	Maintenance (e.g., BIM 7D for Facility Management throughout the building's life cycle)	
R5-Refurbish	Restore products and parts such that they are "like new"	Refurbish elements of the construction (e.g., wooden floor tiles.)	

(*continued*)

Table 2. (*continued*)

9R	Definition	Example in construction	CE approach
R6-Remanufacture	Making the same new products or parts from previously made products and/or parts	Remanufacture elements from previous construction (e.g., using bricks that were previously deconstructed)	
R7-Repurpose	Reusing products and/or parts but with different purposes, whether combined with refurbished	Repurpose elements from previous construction (e.g., using an old door for the top of a table)	
R8-Recycle	Conversion of products and parts to virgin materials and reuse	Recycling materials for avoidance of virgin ones (e.g. plywood)	Useful application of materials
R9-Recover	Energy recovery from materials (also called thermal upcycling),	Recover elements from previous construction (e.g., Construction and demolition waste mass as volume, material incineration)	

3.2 Framework

A building is very different from a usual industrial product, as it contains many different components, made with different materials, with different impacts.

Circular construction supports easy component separation and accessibility, enabling substitutions throughout a structure's lifetime. However, much of the built environment does not align with these principles. In addition, neglecting minor damages, like infiltrations, can result in significant issues if left untreated. Opting to refuse may lead to greater impacts over time, challenging the effectiveness of established hierarchies.

In light of the specified requirements of the construction sector, the Framework for refurbishment and maintenance in Fig. 2, introduces a proposed framework aiming to implement the Waste Hierarchy (WH) and the 9Rs (Reduce, Reuse, Recycle, etc.) in the construction industry, with the primary objective of minimising environmental impacts. This framework offers stakeholders decision support for refurbishing and maintenance of existing buildings. It is based on the Delft ladder [5], but Circular Economy goals are added to waste reduction targets. It includes a multi-level approach considering the building, component, and material level. This framework is yet limited at the material level due to a lack of results from comparative LCA studies assessing different EoL strategies for each material.

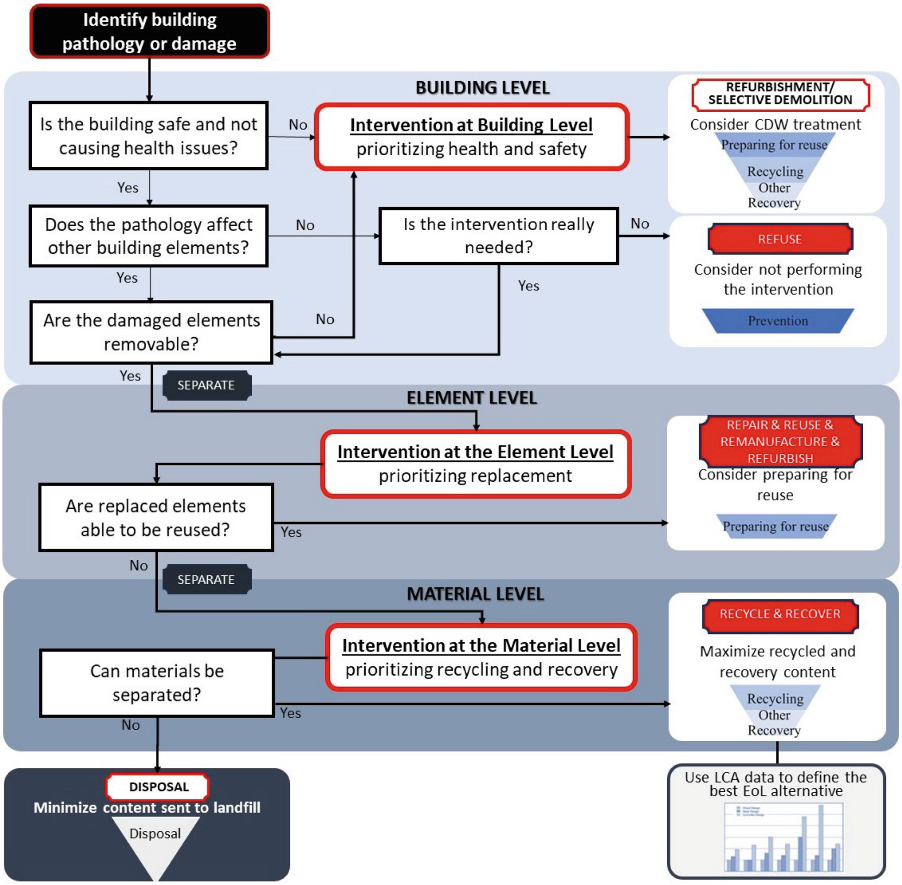

Fig. 2. Framework for refurbishment and maintenance.

4 Discussion

Compared to most other sectors, the construction industry is unique, particularly due to the extensive consumption of resources, the use of different materials, and the prolonged lifespan of buildings. As a result, managing maintenance activities and end-of-life processes within the built environment poses unique challenges.

The association between WFD and 9R, presented in Fig. 1 was previously proposed by Zhang [23]. However, according to the definitions provided by the WFD (a European regulation applied within this geographical boundary), repurposing would be more adequate within recycling due to the change of original purpose. The definitions of the European Union are vague, mainly focusing on waste reduction, raising some concerns about its effective minimisation of environmental impacts. This combination between WH and 9R is suggested to further define and detail the WFD and adapt it to the construction sector, with practical examples.

The proposed framework in Fig. 2, addresses the second goal of this paper, defining a decision framework to guide stakeholders throughout refurbishment and maintenance. LCA results and generic data play a very important role within this framework, better informing about the preferable EoL strategy for each material. However, not all LCAs results meet the requirements because of a general lack of transparency in defining system boundaries, undisclosed origin of inventory data, and absence of sensitivity analysis of assumptions, making them impossible to compare [19]. Another important aspect of LCA results is that they usually cannot be compared due to the assumptions and choices made about the EoL of a product or material. This means that within a certain product's LCA, an EoL strategy, such as recycling, will be considered, but not an alternative EoL strategy, such as reuse or incineration. This absence of comparisons creates uncertainty about the impacts of alternatives, lacking clear guidance on the best EoL strategy for each material, backed by statistical data.

5 Conclusion

Due to the complexity inherent to LCA studies, the WH and 9R seem to be the streamlined approaches to inform decision-makers about the preferable approach aligned with CE principles. Nevertheless, neither approach considers the differences in the impacts of different materials. For that reason, a new framework was proposed to support stakeholders in deciding refurbishing or maintenance alternatives on multiple levels: at the building, component, and material. Four main conclusions can be drawn together:

- The WHD does not discriminate the different types of action contained within, indicating that it might need a new update.
- Separation (of components and materials) should always be considered to enhance the reuse of components and recycling of materials.
- Interventions in the built environment should be preventive and strictly necessary, extending the life cycle of the components and of the building, minimising the need for new materials, and reducing impacts.

Finally, it is important to highlight that comparative LCA at a building scale seems to be difficult, but at the material scale, the assessment could inform about the preferable strategy at the EoL. This paper identifies the need for comparative studies focusing on the EoL of the different materials to support deviation from the WH and inform what the best EoL strategies for each material are.

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