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Article

A Methodology to Qualitatively Select Upcycled Building Materials from Urban and Industrial Waste

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Abstract: The increasing concern about climate change and other planet challenges led society to look for alternatives towards a more balanced relation between natural and built environment. The circular economy emerges as an effective alternative to the linear economic model inspired by natural metabolisms and circulating resources, where their intrinsic value is maintained and improved. This research explores innovative strategies for converting local urban and industrial waste into effective and sustainable building materials. A literature review is conducted on the circular design strategies, re-use and recycle typologies, and waste transformation processes. Then, a methodology for the selection of upcycled and re-used building materials was developed based on the Ashby method and conducted using M-MACBETH. Thirty-five construction solutions on partition walls based on plastic, wood, paper, steel, aluminium, and agricultural waste are discussed. It is shown that ten construction solutions were effective for thermal and acoustic isolation, fourteen for coating, and two for structural functions. Despite their functional limitations, they can be used as building materials, reflecting the enormous potential of waste as a resource for the construction industry.

Keywords: Circular Economy; Multi-criteria decision analysis, Reuse, Upcycle, Industrial Waste, Urban Waste

1. Introduction

Circular Economy (CE) has gained political and scientific significance in recent years indicated as an alternative to the current mainstream industrial capitalism economic model [1]. CE is deemed as an effective method to address social, economic, and ecological issues of the contemporary age and thus achieve the United Nations' Sustainable Development Goals (SDGs) [2].

The relationship between Planet Earth and the Global Economy will be thruly sustainable when the supply of resources and the assimilation of waste considers the environmental limits of the planet [3]. World organisations estimate that production and consumption patterns exceed over 75% of the biocapacity [4]. While 92 billion tons of raw materials were extracted 36 billion tons of waste were produced and collected in 2017 as stated in the Circularity Gap Report. Only 4.2% of these materials were reintroduced into the world economy [1]. These values reflect biodiversity loss, natural resources degradation, and the economic inefficiency of linear systems.

The extraction of virgin resources is predicted to double in the next thirty years [1] due to the growth and consumption patterns of the world population. This trend will lead to a rupture in the supply chain and the volatility of trade prices, especially in the EU, where the industry is highly dependent on international markets. On the other hand, the amount of unrecovered waste illustrates lost economic opportunities in the order of US$ 1,000 billion per year [5]. Construction sector represents 10% of the European Union (EU) GDP [6], accounts for the most significant consumption of virgin resources [7] and produces one-third of all generated waste [8]. The scientific community calls for the need for systemic change addressessing the entire life cycle of buildings and the construction value chain, based on energy efficiency, bio-efficiency, and material efficiency [9].

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In this broader context, new strategies have been developed in the last few years, including bioclimatic architecture, disassembly construction techniques, and sustainable materials evaluation [10]. However, less importance has been given to the cascade recovery or the creative valuation of waste and byproducts from other industries in the construction sector. Open-circuit resource management and industrial symbiosis are effective methods to avoid loss of materials and products value towards an overall economic and social stability. The main challenge is offering construction solutions that are more flexible and cost-effective than traditional construction techniques. This is particularly important within European real estate markets, when raw material stocks are falling, and the global materials supply chain is under pressure [11].

Advanced materials and techniques based on reuse/recycling are emerging on the current market, while designers need to identify the most viable solutions for each specific context. A variety of tools, *e.g.*, building environmental product declaration (EPDs) and product certifications schemes, provide standardised information about the environmental performance of products and materials essential to decision-making [12]. Many scholars have developed sustainable assessment criteria for selecting building materials [13], [14] criteria evaluation, in line with the Circular Economy principles [15]. However, how support the selection of recycled and re-used materials derived from urban and industrial waste is not yet fully explored in literature.

Innovative strategies for converting local urban and industrial waste into building materials and systems are discussed in this study. Its main purpose is to develop a methodology to guide designers' decision-making on upcycled and re-used building materials selection. The proposed methodology is based on the Ashby method and conducted by dedicated software M-MACBETH (*Measuring Attractiveness by a Categorical-Based Evaluation Technique*) [16] [17]. It is capable of handling multiple results generated from qualitative expert judgments, 35 materials and constution solutions from post-consumer waste and byproducts (plastic, wood, paper, steel, aluminium, and agricultural waste) from various industrial sectors are analysed. Then, these solutions are tested in a case study in Lisbon, Portugal. This study aims to address the following questions:

a) *How can designers evaluate and compare a set of environmental and functional performance of upcycled and re-used materials, derived from local urban and industrial waste?*
b) *Are these building systems and materials efficient?*

The first section of the work presents a literature review on design strategies on circular management of regional material flows in the construction sector. The second section reviews re-use and recycle typologies and waste transformation processes. The third section introduces a methodology for selecting upcycling materials and construction systems according to CE principles and evaluates a sample of 35 case studies. Finally, the results are presented based on the sample analysis, and the results are discussed.

2. A Review of Design Strategies for the Circular Management of Material Flows

A circular building is designed, constructed, managed, and constructed following the CE principles [9]. It has the capacity to adapt to the needs of users and the environment and function as a bank, or reservoir, where materials are identified correctly, temporarily stored, and released at the end of their life, optimising the entire value chain with new ownership and business models [18].

This life cycle approach forces designers to adopt a transdisciplinary view and to work on multiple scales and relationships, considering the connections between construction products, the built environment, and the city; and to coordinate stakeholders such as product manufacturers, service providers, and demolition/disassembly companies [19]. Due to this complexity, adopting systems thinking (i.e., understanding the relationship of each part to the whole is and the relationship of the whole to each part in a system) facilitates the coordination of the collaborative network in the value chain, where the architect assumes a central role [20] [9].

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Pomponi *et al.* (2017) propose CE strategies in the built environment through a systems perspective that considers three following levels: macro (national level, cities, general industry structure); meso (regional level/buildings/eco-industrial parks); micro (product level, building components) [9]. However, this systematisation does not present a complete building analysis and comprehension.

Buildings are long-lived entities, often interpreted as large static units but are, in fact, sets of various artefacts, each with its specific life cycle, grouped to respond to a series of requirements and constraints [21]. Consequently, buildings are not managed through their lifecycles as single manufactured products [6]. Indeed, the analysis of buildings over the years reveals that they encompass a sets of dynamic systems that can partially update themselves according to users' needs without becoming obsolete [22]. This phenomenon occurs because a building comprises shearing layers (Site, Structure, Skin, Services, Stuff) responsible for its primary functions. Some of these systems can accommodate changes and transform faster without compromising the others, although poorly, because they were not designed initially functional independent [23].

Designing a building in multi-layers will help approach each system according to specific rules and strategies [24]. Their independence will allow a quick dismantling at the end of building life. However, a building transformation capacity depends not only on functional aspects but also on technical and physical ones. A façade may have a longer lifetime than the systems and components, and these may be incorporated in different technical or biological cycles [25]. Thus, the parts and materials inside a system also need functional, technical, and physical independence allowing necessary transformations at the component and material levels. Within perspective, the "Hierarchy of Material Levels" admits that buildings are hierarchical systems sets responsible for building primary functions [21]. These systems, in turn, are composed of components, elements, and materials [26].

The compression of the buildings as a small piece of a city's metabolism, a living system composed of a series of logically and hierarchically assembled elements, helps organise circular design principles in a top-down approach and then achieve better management and a "wholly independent" and exchangeable" design.

Regarding the "*Hierarchy of Material Levels*", circular strategies are related to specific scales of intervention (Figure 1). Four design strategies that contribute to narrowing and slowing down regional material flows are identified in literature [24], [27] [28]: a) Design with local resources: analyses material flows in the geographic, economic, and social contexts of the city, affecting the choice of elements and materials. b) Design for adaptability (*DfA*): evaluates the correlations between the building and their systems and design for disassembly (*DfD*): assesses relationships between elements, components, and systems. c) Design with sustainable materials focuses on materials and elements.

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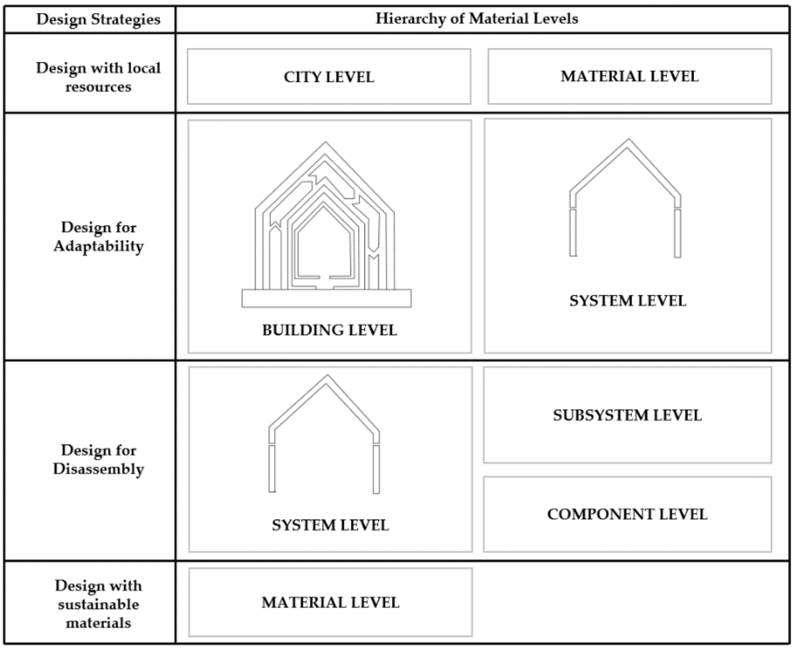

Figure 1. The relationship between Circular design strategies and the "Hierarchy of Material Levels".

2.1. Design with local resources

As stated by Walker *et al.*, the preliminary step in the design of a low environmental impact building is the inventory of locally available materials [29]. Using local building materials will reduce transport impacts, support regional development, and facilitate new circular business models. The Living Building Challenge program defines as a requirement in its certificates that at least 75% of the budget for building materials should come from within a 5000 km radius of the building site, of which 30% should be sourced within 1000 km and 20% within 500 km [30]. The *LEED* v4 in Material and Resource credits include the location valuation factor, which states that Products and Materials should be extracted, manufactured, and purchased within 160 kilometres from the site location of the project [31].

SuperRuse Studios has pioneered the online platform Harvest map, an inventory of local used materials and their location, encouraging architects and designers to explore local resources and the potential of waste and re-use building products available in the region [24]. Analogously, the REPAIR project, and the REFLOW project, among others, introduce the Activity-based Spatial Flow Analysis (AS-MFA)[32]. This methodology aims to connect the spatial, material and social analyses relating to material flows and stocks from waste production. It determines the qualitative and quantitative waste flow specifications in content, space, and time; and analyses the relations between businesses and consumers. Allowing the identification of locally extracted and manufactured resources, possible exchanges of byproducts and wastes between industries (industrial symbiosis) and re-used recycling strategies [32].

2.2. Design for Adaptability (DfA)

The Design for Adaptability (DfA) concept defends those buildings must be adaptable as living systems to remain resilient and respond to the demands of the environment and the users [33]. The valuable life ends with its inability to accommodate changes [28]. Thus, buildings' obsolescence results from an incompatibility between demands and the capacity for transformation [33]. On the demand side, and from a social perspective, there are three types of actors: Society, Owners, and Users. Furthermore, on the capacity side, influenced by technical and physical characteristics, we have Location, Building, Systems, and Components [34]. Schmidt III *et al.* propose a method for assessing fit structures that

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consider six types of change, driven by: the real estate market, performance, use, location, size, and space [33]. Other academics, such as Geraedts, developed key performance indicators for designers to assess the adaptive capacity of buildings [34]

2.4. Design with sustainable materials

The selection of building materials in compliance with sustainability standards reduces construction impacts and ensures that products circulate in efficient and healthy flows [35]. The CE concept clearly distinguishes biological and technical materials (Figure 3). The former consists of natural resources free of toxic substances that can be absorbed by the biosphere, such as wood or sand [36]. The CE model proposes that biological materials can be 'cascaded' through various uses, *e.g.*, solid timber can be transformed into panel products. The latter are manufactured resources that nature cannot assimilate, such as metals and plastics. Technological materials should be retained within industrial loops to ensure they are not discarded in the environment and lost to the economy but re-used and recycled [36]. The Cradle to Cradle (C2C) Certified TM product has four main categories to assess materials and circular products: the Material Health - identifies chemical ingredients of every materials, avoiding chemicals harmful to humans and the environment present on the "Red List"; the Material Re-Use - evaluates if design enables a safe return to nature or industry, and the Renewable Energy and Carbon Management promote renewable energy, and reduced CO_2 emissions; Water Stewardship safeguard clean water resources; and Social Fairness from contributing to equitable society [37].

3. Upcycling waste and byproducts as construction Materials

Since the European Waste Framework Directive (2008/98/EC) - recently replaced by Directive 2018/851/EU - wastes have assumed an increasing role in manufacturing processes [38]. The rational use of natural resources and keeping materials, components, and systems at their highest value as long as possible has progressively been prioritised. The Communication on resource efficiency opportunities in the building sector (COM (2014) 445 fin. l) and The Circular Economic Action Plan identify product design and product policies as one of the main enablers to implement CE. Furthermore, these set long-term targets to reduce landfilling and increase recycling and re-use [39] [40].

Until the 20th century, many components were customised and designed by architects with local techniques and materials. The secondary materials market was the primary supplier due to the scarcity of resources available. Thus, many buildings were constructed with locally recovered materials, such as the medieval constructions where masonry from Roman ruins was used [41]. Even today, many communities and informal settlements In developing countries are built with creative and ingenious solutions from locally available waste and used materials.

Throughout the 20th and 21st centuries, several architects have explored re-use and recycling through different creative processes. John Harbraken overcame the design limitation and the original function of products on re-use and developed a Heineken beer bottle that could be re-used after consumption as an affordable house-building brick [42]. Michael Reynolds back in 1972, built the Thumb House, the first of several homes built on throughout his career. The architect explores a new living concept focused on resource self-sufficiency (materials, water, and energy) and uses waste from nearby landfills as construction materials [43]. Furthermore, research groups such as Vandkunsten Architects [44], Arup - Global Advisory, Design, Planning & Engineering[45], University of Brighton [46] have been working on full-scale prototypes and new practices of re-using building components and materials according to the principles of reversible construction.

Re-use is defined as repeated use of a product, component, or material for the same or a different purpose from initial use. It includes minor changes that allow it to perform a function, *e.g.*, a wooden structure is refurbished to be used again as a wooden structure or a panel [47] [48] [49]t is also relevant to underline the definition of Superuse, which

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means recapturing the value of products when they have the lowest possible profit by giving them new functions and reintroducing them into new cycles with intelligent and creative architectural and Design applications [50].

Recycling is defined as the process of transforming a material so that it can be reintegrated into a new production line as raw material, marking the end of the cycle and the beginning of a new one [47]. The main distinction between re-use and recycling is irreversibility: the material does not return to its original form. Recycling can go in two ways: downcycling - the transformation resulting in a material with a lower value; and upcycling - transforming into a material with a higher value than the initial one; for example, the upcycling of ferrous blast-furnace slag (Fe-BFS), a byproduct generated from siderurgic pyroprocessesto develop active ceramic anodes [51], and the composite material, which has as raw material adhesive and sticker printing waste produced by UPM Biocomposites, Lahti, Finland, and used by architect Shigeru Ban for the furniture company Arteck Milan in 2007[52]. Downcycling is the most widely used transformation process despite being the least beneficial loop in the waste management hierarchy. Re-use saves 88% of greenhouse gas emissions and optimises several tested environmental indicators compared to recycling [53][54].

Literature review and practical cases analysis make it possible to identify patterns and distinguish the six variants in re-use and upcycling transformation processes that convert waste into new building materials [52], [55],[60], [61],[56], [57] described below:

c) *Simple Transformation Process*: it is a creative design process that gives new functional value to waste, including small changes such as cutting, polishing, painting, or screwing. It can be executed on the construction site. The Resource Rows Apartments from Compenhaga Lendeger Group project is an example of creative re-use. The architects have developed an innovative system for re-using brick walls, which involves cutting the walls into sections giving rise to panels. The panels are then fitted into a steel structure, creating different façade compositions [6261].
d) *Design Transformation Process*: The Design of products to never become waste, i.e., after their useful life, they are in a constant state of re-use. They maintain their shape, properties, and composition during their life cycle, except for their function, which can change drastically [52].
e) *Densification Transformation Process*: is a compaction process of waste. In some cases, the compression process activates a specific potential, as is the case with some agricultural waste which, when under pressure, releases a natural glue that can be an asset to produce straw panels, columns, or beams [52]. It involves industrial equipment or more rudimentary systems to compress the waste, and it can be carried out at the construction site [52].
f) *Cultivation Transformation Process*: The metabolism of these materials enables natural recycling processes that can be carried out locally with simple production techniques. Most absorb carbon dioxide during growth, need controlled humid environments, and feed on other waste or materials. The growth process is halted when the material reaches the required density and strength [55]. The material developed by the University of Cape Town in South Africa in 2018 is an example of this transformation process that uses human urine to create building blocks through "microbial carbonate precipitation" [59]
g) *Reconfiguration Transformation Process*: Involves grinding, sewing, glueing, thus changing the original form of the material. Usually, the reconfiguration combines other organic components, inorganic or mineral adhesives. This method can alter the material's density and aesthetic qualities by manipulating the size of the pieces, the grinding, and the resins. It requires specific production processes and industrial machinery that consume energy and release carbon dioxide and cannot be executed on construction sites [52].

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h) *Molecular Transformation Process*: Involves changing the molecular state of the waste. The transformation uses high-tech procedures involving, for example, liquefaction or gasification of the original material to create an element with specific properties. An example of this process is transforming organic waste into bioethanol [38]. This process is carried out in specialised factories as in the previous case.

Table 1. Overview of practical examples of the identified re-use and upcycling transformation processes.

Transformation Processes	Recycling or Re-use	Practical Examples
Simple Transformation Process	Re-use	Facade from The Beehive project, Luigi Rosselli Architects, 2018, Sydney [60]; Resource Rows Apartaments, Compenhaga Lendeger Group [6261].
Design Transformation Process	Re-use	WaterBrick,Wendell Adams [61]
Densification Transformation Process	Re-use	PHZ2, Dratz & Dratz Architects, Oberhausen, Germany[52]
Cultivation Transformation Process	Re-use	Bio brick made from human urine, the University of Cape Town in South Africa [39].[39].
Molecular Transformation Process	Upcycling	WasteBasedBricks®, StoneCycling [68][68]

2.3. Design for Disassembly (DfD)

The design for disassembly (DfD) advocates the undamaged recovery of materials, components, and systems during and after the building's lifetime, replacing current demolition practices [14][24][26]. It challenges the previous importance of recycling, stating that re-use systems have the highest rank and recycle materials the lowest (Figure 2) [64]. Thus, the hierarchy prioritises recovery at the highest levels of the building product hierarchy to preserve the embodied value of systems and components [28]. Durmisevic's Transformation Capability scheme introduces the fundamental assumptions for granting dynamic and dismountable structures [21]. It is necessary to consider the criteria of functional, technical, and physical decomposition. The functional decomposition evaluates the logical organisation of elements in an assembly and the functional autonomy of each element. The technical and physical decomposition evaluates the synchronous assembly of systems, the life cycle of components, the design of interfaces, and the connections type [21]. ISO 20887 standard on design for deconstruction and adaptability provides an international tool to assess deconstruction [66]. Furthermore, research projects such as Buildings as Material Banks (BAMB) [67] offer essential support instruments.

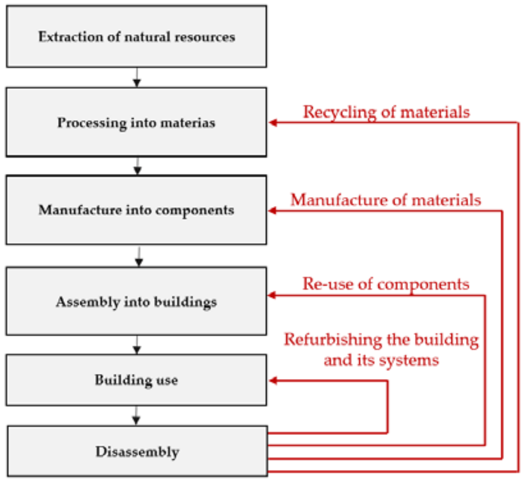

Figure 2. Recycling hierarchy, based on [64]. In order to preserve the embodied value of systems and components, the hierarchy of recycling prioritises building and systems refurbishing and components re-use.

4. A methodology for the screening and selection of waste for building materials

A methodology is proposed in this research for selecting re-used and upcycled building materials and systems from post-consumer waste and byproducts. The methodology is demonstrated on buildings' internal partition walls through its application.

This methodology is an extension of Ashby material selection method [35]. According to the author, selecting materials involves seeking the best match between the design requirements and the material's properties. Ashby's methodology has four main stages. It is then complemented with the pre-defined environmental criteria for re-used and recycled materials and a Multi-Criteria Decision Analysis. The four steps are described below and represented in Figure 4:

1. The *translation of requirements* defines the function of the material, the requirements necessary to achieve it, and identifies the non-negotiable ones.
2. The *screening process* involves eliminating the materials that do not meet the performance requirements; in the classification, the materials are sorted according to their ability to meet the established requirements.
3. The *rank process* involves evaluating the materials that survive the screening step, with criteria of excellence.
4. The outcome of the steps is a ranked shortlist of candidates that meet the constraints and are most highly rated. Then it is necessary to seek the documentation information in handbooks, suppliers' datasheets, websites of environmental agencies, and other high-quality websites

In the first phase, to assess and compare the sustainability and functionality of different solutions, it was necessary to synthesise the principles of the circular economy into performance requirements and criteria; and functional performance requirements and criteria were defined according to the building's material function.

The Multi-Criteria Decision Analysis (MCDA) was used to assist the screening process due to the multiple and heterogeneous criteria proposed. Macbeth (Measuring attractiveness by a Categorical-Based Evaluation Technique) method is used in this research for its ability to incorporate many preferences built through pairwise comparison judgments. It allows a participative evaluation, providing a complete ranking through an additive aggregation approach, and possible variations of judgements, performances, and weights on the model [16] [17].

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After defining criteria and performance levels, a panel of experts (in this case, architects and civil engineers) judged the performance requirements for each sub-component of the wall. Then, the panel of experts defined the difference of attractiveness between the performance levels of each criterion and between different criteria. This set of criteria-wise was numerically ranked in terms of attractiveness. Then, all options (construction solutions) were classified according to the defined performance levels, and the software, through weighted average, delivers the ranking of all the options in a 0-100 scale.

In the following sections, we expand each methodology step and demonstrate its application to internal partition walls. The demonstration on this practical case study was based on the fact that according to the concept of "shearing layers", Partition walls are systems part of the Space Plan, which have a life expectancy of 3 to 30 years [17]. Thus, they have a relatively short life expectancy and will be upgraded or replaced more frequently, representing a more active market. On the other hand, they require less demanding structural and weather resistance constraints than other systems.

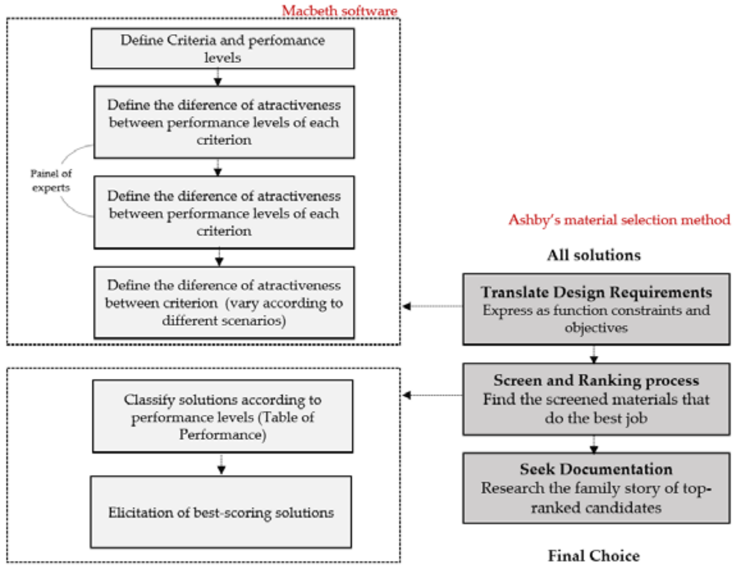

Figure 3. Methodology to select building materials and systems that transform post-consumer waste and byproducts, proposed in this research.

4.1. Translation of functional requirements

The functional performance defines the required level of material efficiency, which is different for each building component. Strength, deformability, and durability along the whole life of the building are fundamental parameters especially in load-bearing elements. The components of the façade system are waterproofing, hygrothermal properties, and so on. The following parameters were considered, and the performance level of each criterion was systematised in Table 2:

- *Mechanical Resistance Capacity* defines the material behaviour when subjected to mechanical stresses; thus, it is associated with its ability to withstand an applied forces without breaking or deforming.
- *Thermal performance* measures the thermal capacity and heat transfer capacity to ensure thermal comfort and measure energy efficiency in the building.
- *Acoustic performance* is the ability of a material to absorb or insulate sound.
- *Water-resistance* is the ability of a material to maintain its properties when exposed to water in the long term. Some materials lose their properties when exposed to water,

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negatively impacting performance. Usually, if a material absorbs water, its size expands, the thermal conductivity increases, and strength and durability can be compromised.

- *Fire Resistance* characterises the behaviour of a material when exposed to fire, such as toxic gas and smoke emission. The importance of classifying this property is to ensure the safety of the occupants in case of fire.
- *Durability* is the ability of a material to resist the combined action of physical, chemical, biological factors to which they are subjected. If the material is durable, it will have a longer service life and a reduced need for maintenance.
- *Sensory Properties* identifies the main sensory properties of materials, significant in finishing materials. The main sensorial characteristics of materials are texture, brightness, transparency, and odour.

Table 2. Performance levels for each functional criterion

Mechanical Resistance Capacity	Thermal performance	Acoustic performance	Sensory properties
High Medium Low	High Medium Low	High Medium Low	Texture; Brightness; Colour; Transparency; Odour
Water and moisture resistance	**Fire Resistance**	**Durability**	
Impermeable Hydrophilic water-resistant Hydrophilic non-water-resistant	Non-flammable materials Fire Retardant Materials Flammable materials	Durable Non-Durable	

4.1.1 *Partition walls functional requirements*

The proposed methodology for selecting upcycled and re-used materials is applied to partition walls. The first step is to identify the various functional parts that make the components of a partition wall, integrated into the building, work properly (Figure 5); the second step is to translate their functional needs into requirements and constraints (Table 3). The ability of a material or component to respond to constraints reflects the quality of the interior spaces, namely, the thermal, visual, and acoustic comfort throughout the life of the building.

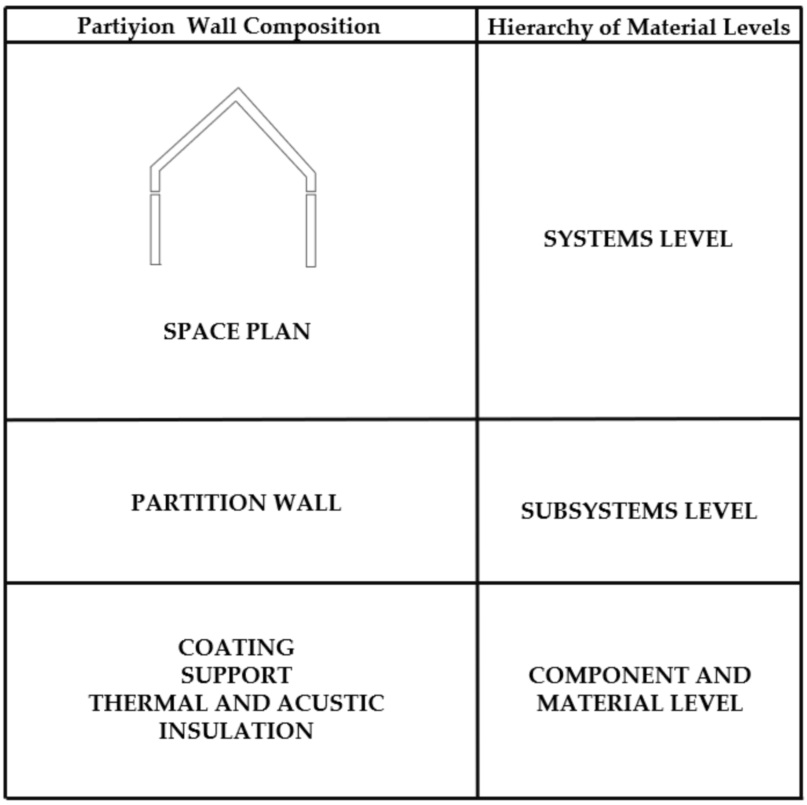

Figure 4. Identification Partition Walls main functions.

The requirements and constraints necessary to achieve all functional demands were qualitatively identified according to their need to respond to the previously defined functional parameters (Table 3). For example, a component responsible for insulation needs good acoustic and thermal performance, moisture, and fire resistance. However, it is not relevant to have an excellent mechanical resistance capacity, unlike a load-bearing component.

Table 3. Identification of Constraints, Objectives of Partition Walls

Functional Parameters	Coating	Thermal Acoustic insulation	Support
Mechanical Resistance Capacity	Indifferent	Indifferent	High
Thermal performance	Indifferent	High	Indifferent
Acoustic performance	High	High	High
Water and moisture resistance	Indifferent		Hydrophilic water-resistant or impermeable
Fire Resistance	Non-flammable or fire retardant	Non-flammable or fire retardant	Non-flammable or fire retardant
Durability		High	
Sensory Properties	It depends, should archive an aesthetic and functional coherence. *	Indifferent	It depends, should archive an aesthetic and functional coherence. * It depends, should archive an aesthetic and functional coherence. *

4.1.2 Translation of the environmental requirements and parameters according to the CE principles

Environmental performance requirements are essential to qualitatively evaluate the circular potential of re-used and upcycled waste materials. The following requirements are considered and categorised in Table 4:

- The *typology of waste* identifies the nature of the waste. Post-consumer waste is composed of urban waste, i.e., waste of domestic origin generated by society in its daily activities. In contrast, industrial waste or byproducts result from industrial production processes or waste from a particular industry, e. g. fly ash from the steel industry or wood scraps.
- The *complexity of the Transformation Process* allows sorting by order of complexity of the transformation processes. It is crucial to prioritise the simpler transformation processes over the more complex ones. The more complex the transformation processes are, the more energy, carbon, and labour are required to produce the new materials and building systems. Generally, the most straightforward transformation processes can be executed on a construction site, eliminating the need for production and transport processes, whereas more complex processes involve a specific production line.
- The *toxic content* identifies harmful substances in materials that may compromise humans and environmental health. The materials used in the circular building must not contain the substances present in Building Industry Red Lists [68]. No prohibited

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products or materials shall be added during the processing processes in this sample, *e.g.*, epoxy resin.

- The *Potential for Reintegration into the Biological and Technological Cycle* allows the identification of the capacity that materials, at the end of the useful life of the building, must be re-used in cascade or eliminated by nature in biological nutrients; or re-used and recycled without losing value in technological nutrients [69]. This criterion identifies if the transformation process does not compromise and promotes continuous material flow.
- The Availability and Local Proximity parameters can be defined at various scales according to the city's political and social geographic context. Three radii of geographical proximity with a centre in Lisbon can be defined for this analysis: High proximity: Radius of 40 kilometres; Medium proximity: 25 kilometres radius; Low proximity: 40 kilometres radius with the centre of the intervention area (figure 5). Different types of waste were identified and divided into five groups according to their nature: plastic, paper, wood, steel/aluminium, and agricultural waste. The relevant stages in managing this waste, the actors involved, and the potential places to obtain this waste in Lisbon were also identified within the defined radius.

Figure 5. Map of the city of Lisbon with the radii represented.

Table 4. Performance levels for each criterion based on experts' judgments.

Typology of waste (T)	Potential for Reintegration into the Biological and Technological Cycle (CTR)	Availability and Local Proximity (PRC)
Urban Waste Industrial Waste	Null Low High	Available within a 10 km radius. Available within a 25 km radius Available within a 40 km radius.
Complexity of the Transformation Process (ALP)	**Toxic Content (TC)**	
Simple Transformation Process (Reuse) Design Transformation Process Densification Transformation Process Reconfiguration Transformation Process Cultivation Transformation Process Molecular Transformation Process	High Low None	

4.2 Weighting of Environmental and Functional performance levels

After defining the environmental and functional performance levels, the experts more clearly defined the distances between the various performance levels to obtain numerical values. The experts defined the difference in attractiveness between two performance levels by selecting the most appropriate adjective from seven semantic categories defined in Macbeth method: *no, very week, week, moderate, strong, very strong, or extreme* (Figure 6). For exemple Complexity of the Transformation Process difference in attractiveness between *Simple Transformation Process* (S) and *Design Transformation Process* (D) ratings was *very weak*. In contrast, *Cultivation Transformation Process* (C) and *Reconfiguration*

Transformation Process (R) ratings attractiveness was *strong*. The exact process was carried out to define the weights of each criterion according to each partition wall component. Three design scenarios were defined, when the dominant aim is thermal and acoustic insulation, cladding, and supporting materials (Figure 7).

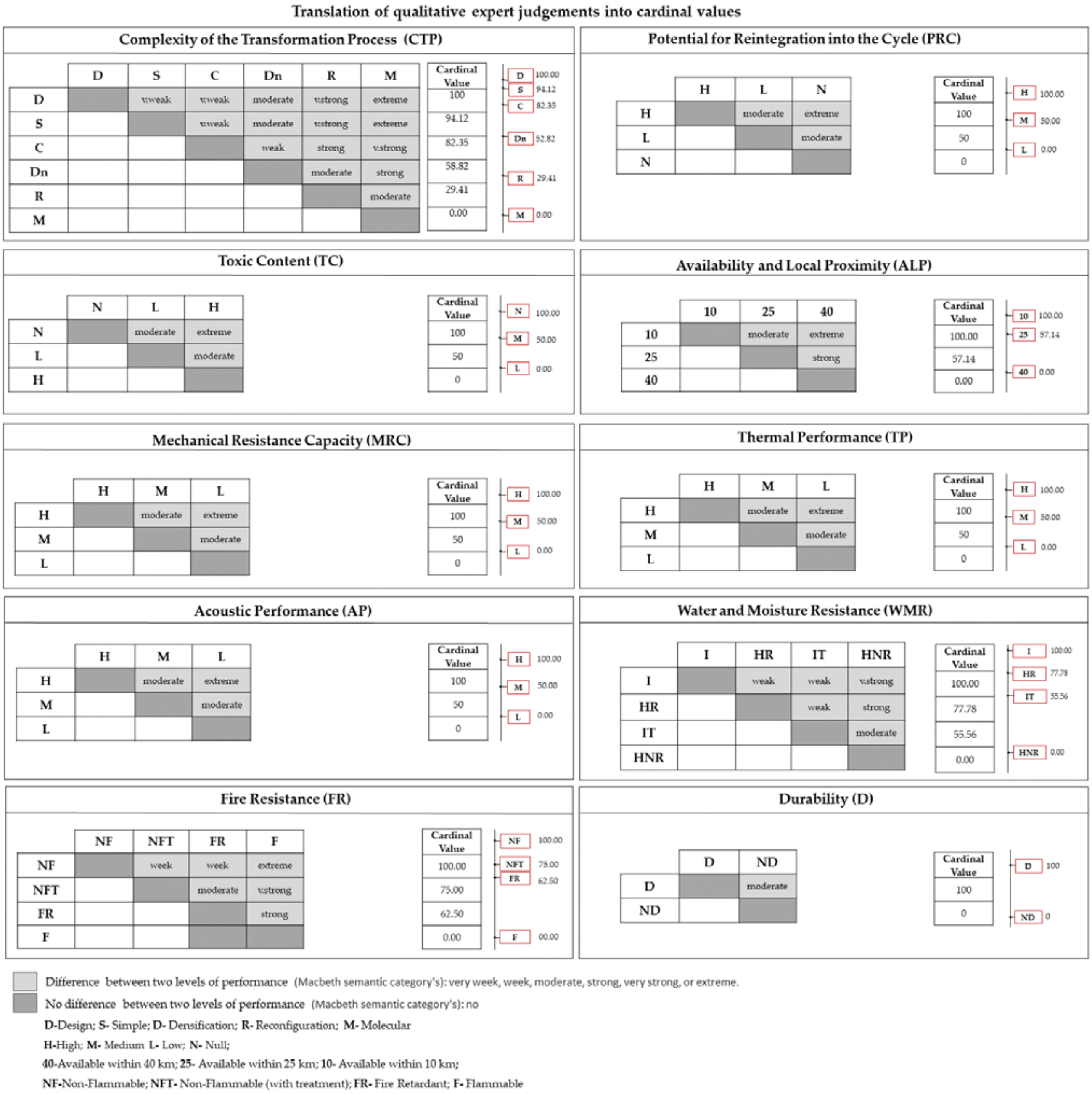

Figure 6. Macbeth judgment matrices related to the difference of attractiveness between the performance levels.

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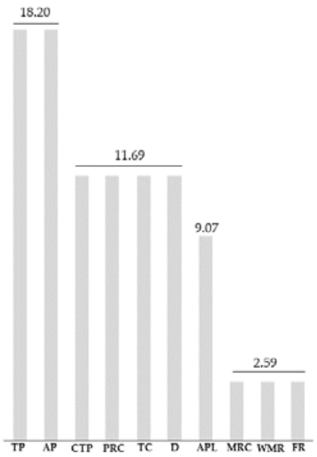
Translation of qualitative expert judgements into cardinal values

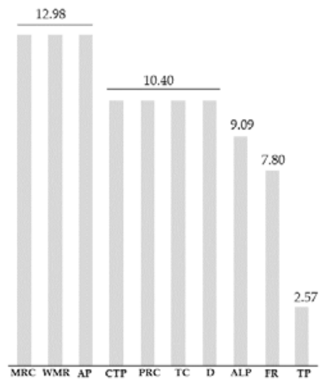
1st Scenario: Thermal and Acoustic Isolation

	TP	AP	CTP	PRC	TC	D	APL	MRC	WMR	FR	Cardinal Value
TP			strong	strong	strong	strong	v.strong	extreme	extreme	extreme	18.20
AP			strong	strong	strong	strong	v.strong	extreme	extreme	extreme	18.20
CTP							weak	v.strong	v.strong	v.strong	11.69
PCR							weak	v.strong	v.strong	v.strong	11.69
TC							weak	v.strong	v.strong	v.strong	11.69
D							weak	moderate	moderate	moderate	11.69
APL								moderate	moderate	moderate	9.07
MRC											2.59
WMR											2.59
FR											2.59



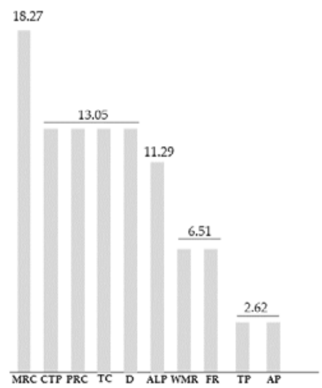
2st Scenario: Coating

	MRC	WMR	AP	CTP	PRC	TC	D	ALP	FR	TP	Cardinal Value
MRC				weak	weak	weak	weak	moderate	moderate	extreme	12.98
WMR				weak	weak	weak	weak	moderate	moderate	extreme	12.98
AP				weak	weak	weak	weak	moderate	moderate	extreme	12.98
CTP								v.strong	v.strong	strong	10.40
PRC								v.strong	v.strong	strong	10.40
TC								moderate	moderate	strong	10.40
D								v. weak	moderate	strong	10.40
ALP									v. weak	strong	9.09
FR										strong	7.80
TP											2.57



2st Scenario: Support

	MRC	CTP	PRC	TC	D	ALP	WMR	FR	TP	AP	Cardinal Value
MRC		weak	weak	weak	weak	moderate	strong	strong	v.strong	v.strong	12.98
CTP						v. weak	moderate	moderate	strong	strong	12.98
PRC						v. weak	moderate	moderate	strong	strong	12.98
TC						v. weak	moderate	moderate	strong	strong	10.40
D						v. weak	moderate	moderate	strong	strong	10.40
ALP							weak	weak	moderate	moderate	10.40
WMR									v. weak	v. weak	10.40
FR									v. weak	v. weak	9.09
TP											7.80
AP											2.57



Difference between two levels of performance (Macbeth method): very week, week, moderate, strong, very strong, or extreme.
No difference between two levels of performance (Macbeth method): no

CTP-The Complexity of the Transformation; Process **PRC**-The Potential for Reintegration Into The Biological and Technological Cycle; **TC**-The Toxic Content **ALP**-The Availability and Local Proximity; **MRC**-The Mechanical Resistance Capacity; **TP**-The Thermal Performance; **AP**-The Acoustic Perfomance **WMR** - The Water and Moisture Resistance **Fr**-The Fire Resistance **D** -The Durabilityz

Figure 7. Macbeth judgment matrices related to the attractiveness difference between each criterion (three scenario models were developed according to the different components of partition walls).

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4.3. Classification process

The samples collected in this study comprises materials/construction systems upcycled or re-used from post-consumer and industrial waste. These were divided into five groups: plastic, paper, wood, steel/aluminium, and agricultural waste. Thirty-five case studies are selected and classified according to performance levels previously described.

Table 5. Performance levels of the materials ans construction solutions from plastic waste.

Environmental Parameters							Functional Parameters						
Sample	**Ref.**	**T**	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
ARTEK PAVILION, Shigeru Ban Architects, Paris, France	[55]	T1 Sticker Printer Waste	Reconfiguration	High Technological Cycle	Null	10 Km	Medium	Low	Low	Impermeable	B1 Fire Retardant	Durable	Smooth, Spleen, Colour Gray, Transparent,
BYFUSION BYBLOCK, UPM Bio composites, Lahti, Finland	[70]	T1 plastic waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Flammable	Durable	Irregular Texture, Spleen, Opaque, Odourless
POLLI-BRICK MINIWIZ, Taipei, Taiwan	[71]	T1 PET Bottles	Design	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Glossy Translucid, Colour Gray, Odourless
RECY BLOCKS, Gert de Mulder	[52]	T1 Plastic Bags	Reconfiguration	High Technological Cycle	Null	10 km	Low	Low	Low	Impermeable	Flammable	Durable	Smooth, Spleen, Colour Gray, Transparent, Odourless
Bima's Microlibrary, Indonesia, SHAU Bandung	[72], [73]	T1 Ice Cream Boxes	Simple	High Technological Cycle	Null	10 km	Medium	Medium	Low	Impermeable	Flammable	Durable	Texture with Geometric Pattern, Glossy, Translucid, White, Odorless
Pet Pavilion, Project.DWG e LOOS.FM, Netherlands	[74]	T1 PET Bottles	Simple	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Flammable	Durable	Texture Smooth, Glossy, Translucid, Blue and White, Odorless
PET WOOL, SupaSoft Insulation UK	[75]	T1 PET Bottles	Reconfiguration	High Technological Cycle	Null	10 km	Low	High	High	Hydrophilic water-resistant	Non-Flammable	Durable	Irregular Texture, Glossy, Opaque, White, Odorless

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Table 6. Performance levels of the materials ans construction solutions from paper waste.

			Environmental Parameters				Functional Parameters						
Sample	**Ref.**	**T**	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
Corrugated Cardboard Pod, Rural Studio, Auburn University, Newbern, AL, USA	[52]	T1 Cardboard waste	Densification	High Technological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Fire Retardant	Not Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
PHZ2, Paper recycling facilities, Oberhausen, Germany	[52]	T1 Cardboard waste	Densification	High Technological Cycle	Null	10 km	Low	High	High	Impermeable with treatment	Fire Retardant	Not Durable	Irregular Texture, Dull, Opaque, Coloured, Odourless
PAPER TILE VAULT, BLOCK Research Group, ETH Zurich, Switzerland	[52]	T1 Cardboard waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	High	Impermeable	Non-Flammable	Not Durable	Texture Irregular, Dull, Opaque, Beige, Odourless
Newspaper Wood, Mieke Meijer with Vij5, Eindhoven, The Netherlands	[76]	T1 Newspapers	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Non-Flammable	Durable	Irregular Texture, Spleen, Opaque, Coloured, Odourless
TUFF ROOF, Daman Ganga Paper Mill, Gujarat, India	[52]	T1 TetraPack Packaging	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable	Fire-retardant	Durable	Irregular Texture, Glossy, Opaque, Coloured, Odourless
REMATERIALS ROOF PANELS, Hasit Ganatra and Swad Komanduri,	[52]	T2 Paper Packaging and Agricultural Waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Medium	Low	Impermeable	Flammable	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless
ECOR, Robert Noble of Noble Environmental Technologies, San Diego, CA, USA	[77]	T1 Cardboard Waste	Reconfiguration	High Biological Cycle	Null	10 km	Medium	Medium	Medium	Impermeable with treatment	Non-Flammable with treatment	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

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Table 7. Performance levels of the materials ans construction solutions from wood waste.

			Environmental Parameters				Functional Parameters						
Sample	**Ref.**	**T**	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
PAVILLON CIRCULAIR, Encore Heureux, France	[78]	T1 Doors and furniture	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable with treatment	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
POLISH PAVILION AT MILAN EXPO 2015, 2PM Architekci	[79]	T1 Fruit Boxes	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
Ami-Lot, Malka Architeture	.[80], [81]	T1 Palettes	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treatment	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
Vegan House Fachade, Block Architecs, Vietname	[82]	T1 Blind	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
Collage house Fachade, S+PS Architects, India	[83]	T1 Doors	Simple	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
SongWood Engineered Timber Resources, Boulder, CO, USA	[84]	T2 Carpentry waste	Reconfiguration	Low Biological Cycle	Low	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Brown, Odourless
Wood Foam, Fraynhifer Instituit for Wood Research	[55][85]	T2 Carpentry waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Hydrophilic water-resistant	Non-Flammable with treatment	Durable	Irregular Texture, Dull, Opaque, Brown, Odourless

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Table 8. Performance levels of the materials and construction solutions from steel/aluminium waste.

			Environmental Parameters				Functional Parameters						
Sample	**Ref.**	**T**	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
D3 Abwab Pavilion, Lot-el, South Africa	[86] [87]	T1 Industrial containers	Simple	High Biological Cycle	Null	10 km	High	Low	Low	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Odourless
Dubai Design Week 2015 Pavilion, Fahed Architects	[88]	T1 Springs for collisions	Simple	High Biological Cycle	Null	10 km	High	Low	Low	Impermeable with treatment	Non-Flammable	Durable	Irregular, Glossy, Translucent, Copper Odourless
Can Cube, Archi-Union Architects, Xangai	[89]	T1 Aluminium Cans	Simple	Low Biological Cycle	Null	10 km	High	Low	Low	Impermeable	Non-Flammable	Durable	Geometric Pattern, Dull, Opaque, Brown, Odourless
ALKIMI, Renewed Materials, LLC, USA	[90]	T2 Aluminium and acrylic waste	Reconfiguration	High Technological Cycle	Null	10 km	Medium	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Colored ,Odourless
Alusion–Stabilized Aluminium Foam Panels, Cymat Technologies Ltd., Mississauga, ON, Canada	[91]	T2 Scrap	Molecular	High Technological Cycle	Null	10 km	High	Low	Medium	Impermeable	Non-Flammable	Durable	Smooth, Dull, Opaque, Gray, Odourless

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Table 9. Performance levels of the materials and construction solutions from agriculture waste.

Environmental Parameters							Functional Parameters						
Sample	**Ref.**	**T**	**CTR**	**PRC**	**TC**	**ALP**	**MCR**	**TP**	**AP**	**WMR**	**FR**	**D**	**SP**
TRAshell e Bio-flexi|Plant Cultur	[92]	T1 Cardboard waste	Reconfiguration	Low Biological Cycle	Low	10 km	Medium	Medium	Medium	Impermeable with treat-ment	Non-Flamma-ble	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless
AGRICULTURAL WASTE PANELS	[55]	T1 Agriculture Waste	Reconfiguration	High Biological Cycle	Null	10 km	Medium	Low	Medium	Impermeable with treat-ment	Flamma-ble	N.Durable	Geometric Pat-tern, Dull, Opaque, Brown, Odourless
HY-FI, Ecovative, Green Island, NY, USA	[93], [94]	T1 Agriculture Waste	Cultivation	High Biological Cycle	Null	10 km	Medium	High	High	Impermeable with treat-ment	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless
Mycoform,, Terre-form ONE, New York City, NY, USA	.[93], [95]	T1 Agriculture Waste	Cultivation	Low Biological Cycle	Null	10 km	Medium	High	High	Impermeable with treat-ment	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless
THE GROWING PAVILION, The Living, New York City, NY, USA	[96], [97]	T1 Agriculture Waste	Cultivation	High Biological Cycle	Null	10 km	Low	High	High	Impermeable with treat-ment	Non-Flamma-ble with treatment t	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless
DECAFE TILES, Raul Lauri Design Lab	[52]	T1 Coffee dregs	Reconfiguration	High Biological Cycle	Null	10 km	Low	Low	Medium	Impermeable with treat-ment	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Coffe
WINE CORK TILES, Yemm & Hart Green Mate-rials, Marquand, MO, USA	[52]	T2 Wine corks	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Impermeable (with treat-ment)	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless
SUNFLOWER ENTREPRISE, Thomas Vailly, Holand	[98]	T2 Sunflower production waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	High	High	Impermeable with treat-ment	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Green, Odourless
CHIP [S] BOARD, Rowan Minkley Robert Nicoll, Netherlands	[99]	T1 Potato Waste	Reconfiguration	High Biological Cycle	Null	10 km	Low	Medium	Medium	Impermeable with treat-ment	Non-Flamma-ble with treatment	N.Durable	Irregular Tex-ture, Dull, Opaque, Brown, Odourless

To assess the parameter The Availability and Local Proximity (APL), the relevant stages in managing waste flows, the actors involved, and the potential places to obtain this waste in Lisbon had to be identified. Table 6 summarises this process for plastic waste; in Appendix B, the tables for all waste flows are represented. It should be emphasised that urban post-consumption waste (bottles, cans, objects, and food) is placed in undifferentiated or recycling containers, collected and sorted by municipal collectors, and forwarded to the respective waste treatment and recovery centres. Therefore, these are the most likely places to obtain urban waste in large quantities. Objects that have a longer useful life (doors, tables, chairs, kitchen utensils) can be found in second-hand shops, online second-hand sales platforms, and specialised repositories such as the Repositório de Materiais [[100]. Regarding industrial waste, the best place to get this waste is from the company that generates it, so contractors or building materials companies can establish a beneficial relationship with that industry.

Table 10. Identification of the relevant stages of the production chain, authors involved, and places to obtain the plastic waste in Lisbon, in Appendix B, the tables for all waste flows are represented.

Typology of waste and Symbology			Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Plastic	Urban Waste	PET Bottles	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul – Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul - Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha •Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar - Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo - Tratamento Resíduos Sólidos Eim - Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo • Recipolymers, Reciclagem de Polímeros, S.A.; Arranhó
		Various types of plastic waste	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	
		Plastic bags	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	
		Containers to preserve food	Consumption Collection Sorting Waste treatment	Municipal Collectors, Waste Treatment Companies	Public waste treatment companies.	
	Industrial Waste	Sticker Printer Waste	Adhesive Paper Production Final Adhesive Printing and Cutting Waste Collection Waste Treatment	Graphics, Sticker Shops Silk Screen Printing. Municipal Collectors Waste Treatment	Public waste treatment companies.	•Cópia Igual- Centro de Informática, cópias e Papelaria, Lda, Benfica •LET'S COPY - Printshops; Saldanha •Azul e Amarelo, Centro de Cópias e Impressão, Chelas •Copy Campus; Alta de Lisboa •Mar de Cópias, Algés •Diolicopia-Centro De Copias, Lda; Benfica •Zoomcópia, Saldanha •Centro de Cópias Arco Íris de Pedro Proença, Lda, Campo P. •CopyCenter Centro de Cópias; Cid.Un. •Reprografia Comercial Planeta Colorido, Campo Grande

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The potential places to obtain this waste in Lisbon are georeferenced in a Harvest map, as shown in Figure 8. The full version of the harvest map is available at Supplementary Materials: Harvest map.

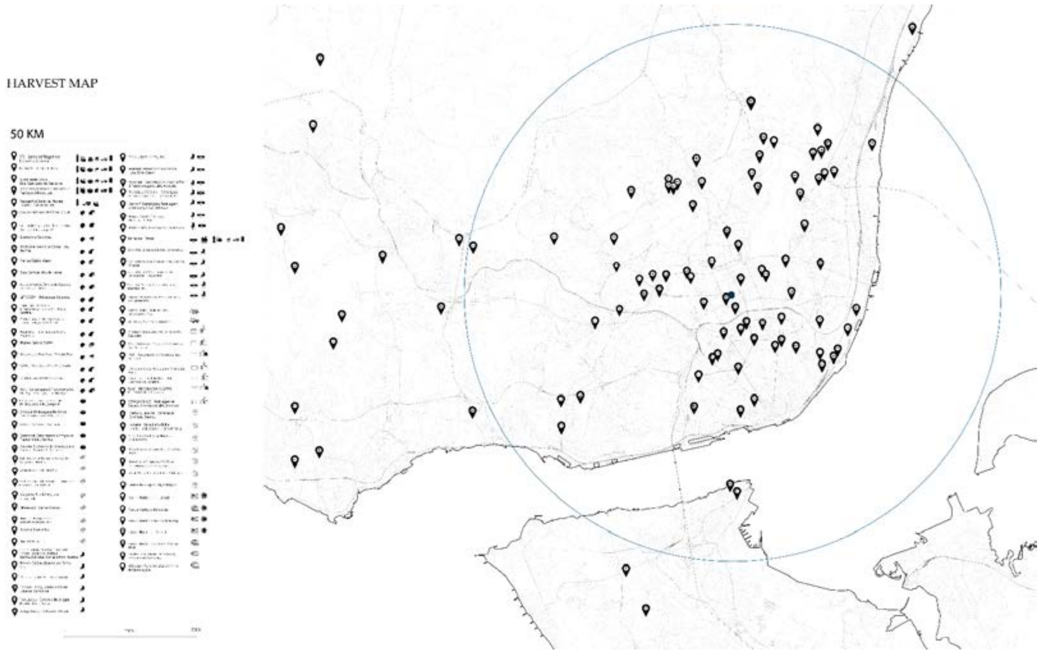

Figure 8. Representation of the harvest map is available for consultation at Supplementary Materials: Harvest map.

4.4. Ranking process

After classifying the 35 materials and construction solutions, Macbeth delivers a ranking score for each option according to the function of the partition wall component (design scenario). Figure 9 shows the overall thermometer, which orders the solutions from the best classification (100) to the worst (0) (Figure 9 and 10). To screening results, all combinations characterised by a global weighted score lower than 75 were discarded on the 1st and 2nd scenario (thermal and acoustic insulation and cladding) and lower than 90 on the 3rd scenario (support). The support function demands a higher set of requirements, and the analyst considered that only those starting from 90 ranks are adequate to perform it; moreover, the difference in the parameters between the best-scoring solutions considerably varies for the others options in the 1st and 3rd scenarios, form 4,69, 2,86, correspondingly.

In the 1st scenario (thermal and acoustic insulation), ten solutions have the best-scoring. Among those, four best-scoring solutions stand out, namely:

a) Wood Foam (89.23) is a product developed by the Fraynhifer Institute for Wood Research in Germany, obtained through lignocellulose from the biomass of trees and other woody plants. The strength of the material does not depend on the quality of the wood. In this sense, the wood can have sawmill waste, forest trimmings and chips as raw material because the strength of the foam is related to the contact between the cross fibres and not their length or fibre quality. It can be produced with different densities from 40 to 200 kg/m3 and "has thermal conductivity levels comparable to expanded polystyrene, around 0.04w/km. Because it is a porous and hygroscopic material, it behaves like a sponge in contact with water and moisture, but the volume of the material remains intact. In general, the wood foam has a high resistance, low thermal conductivity, and good behaviour with fire; in this sense, it can be applied as

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thermal insulation in product packaging, furniture, and non-structural panels. Besides being a product produced from waste, it is 100% organic and recyclable, and it is an effective alternative to foams made from petrochemical products [5962][85].

b) PET wool (88.58) or polyester wool is a thermo-acoustic material made from used PET bottle fibres. It is a 100% recyclable material and is already marketed by some companies. It is manufactured in many thicknesses (300 - 200 mm), has a heat transfer coefficient of 0.04 w/mk, is waterproof, and has excellent sound absorption capacity. It is a material that contains no harmful chemicals or binders and is entirely safe to handle is a non-combustible material [75].

c) Hy-Fi and Mycoform (83.15) are identical materials, composed of agricultural byproducts and mushroom mycelium, which function as a natural digestive glue. This type of cultured material uses the natural growth of fungi as a bio-manufacturing method. The manufacturing process is straightforward; agricultural waste is mixed with water and the living organism (mushroom roots/mycelium). After five days, the mixture can be placed in a closed mould, where it rests for another five to ten days (25-27°C). The roots and organisms grow and fuse into biomass, giving rise to a solid material subjected to heat (70-90°C), hot pressed, oven-dried or dried in the open air to dehydrate the material, interrupting the growth process, and neutralise the fungus. Mycelium composites have a thermal conductivity between 0.04-0.18 W/m-k, which can be optimised using straw and hemp fibres (low density), reducing the values to 0.04-0.08 W/m-k. Mycelium alone can absorb low-frequency sounds (<1500 Hz), outperforming cork [93], [94].

In the 2nd scenario (coating), fourteen solutions had the best-scoring. Among those, the four best-scoring solutions stand out, namely:

a) Polli-Brick (93.99) from the companies Winimiz are 100% recycled Polyethylene Terephthalate polymer bottles, designed to be re-used directly in construction, as a translucent, lightweight after consumption and recyclable material. The design of the bottles is modified in 3D into a modular honeycomb-like shape, resulting in a very sturdy container that is suitable for the construction industry, and was used in the iconic EcoARK building at the 2010 International Flora Expo in Taipei, Taiwan [71].

b) Vegan house atelier Block Architects and Collage House Facade (91.00) Both projects have similar concepts; the architects composed the facades of both houses with blinds and doors used and collected locally [82] [83].

c) 3D Abwab Pavilion (91.00) designed The Lot-el studio *is* located in the Maboneng district in South Africa. The building consists of 140 stacked containers connected with the usual twist lock and welded together. These function as the structural element of the entire building; only structural reinforcement was added in the gallery spaces. Each residence consists of two or three containers [86] [87].

On the 3rd (support)scenario, it was possible to identify two solutions with the best classification., namely:

a) 3D Abwab Pavilion 8 (93.88)

b) Dubai Design Week 2015 Pavilion (91.10). Fahed Architects was invited to design a temporary pavilion for Dubai Design District with materials from a local waste management company, Bea'ah. The architects designed the pavilion to be a work of innovative art and creative expression. The pavilion was composed of 1100 springs from used mattresses. The architects chose this residue for its strength, lightness and silhouette. The springs had the function of an organic (cloud-like) structural mesh that controlled natural light and recreated patterned shadows on the floor. At the end of the exhibition, the pavilion was dismantled, and materials were returned to Bea'ah [88].

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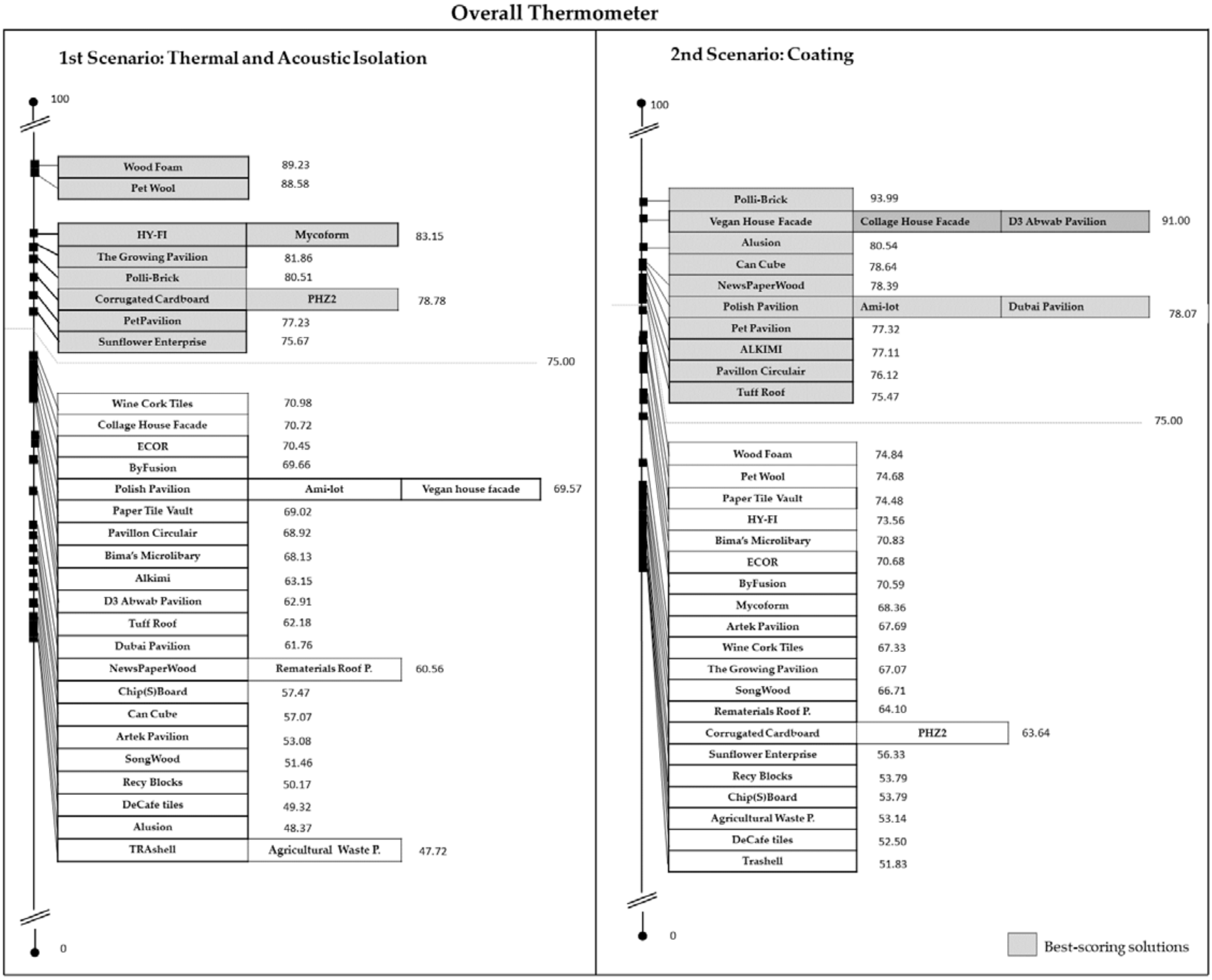

Figure 9 Visual scoring in 1st and 2nd scenario

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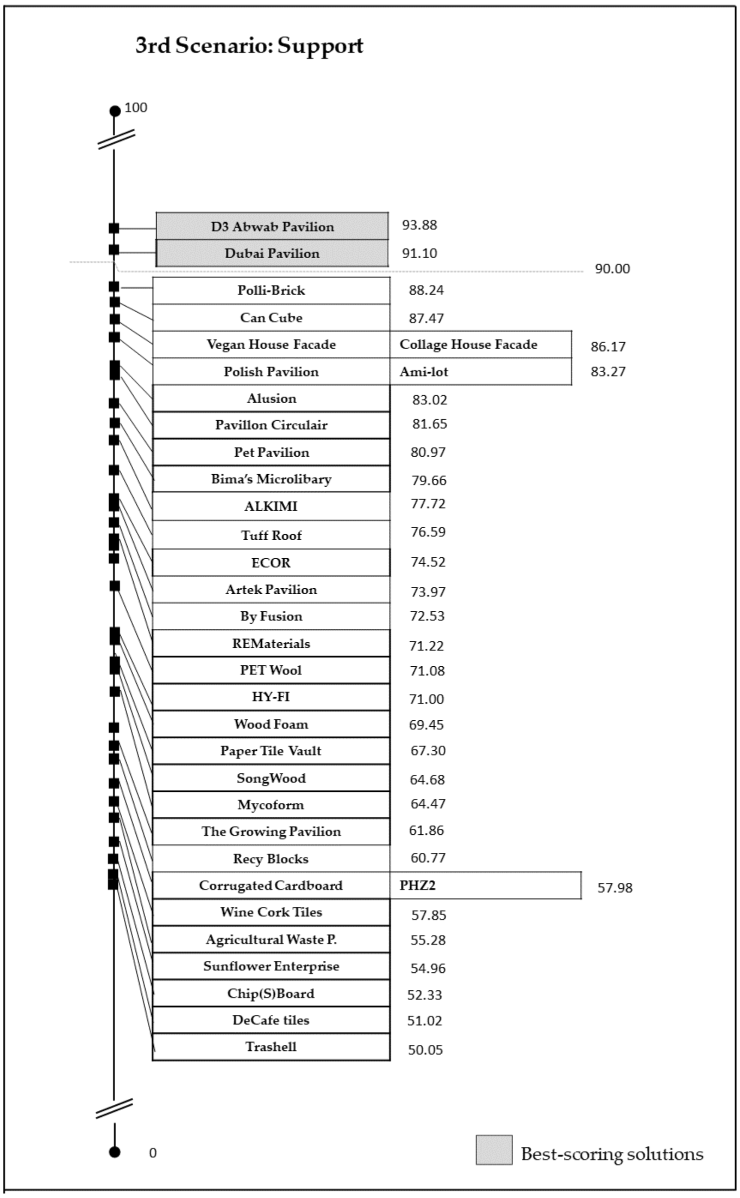

Figure 10 Visual scoring in 3rd scenario

5. Discussion

The overall thermometer revealed several hypotheses for each established scenario (Table 6). The plurality of the sample can perform the functions of cladding and acoustic insulation but with significant functional limitations, especially in structural functions. The case studies made from paper waste nature have the most limitations from a constructive and environmental point of view. They are not durable materials that have low mechanical resistance and water resistance. Generally, virgin materials such as harmful glue or resin need to be added during the transformation process to archive an adequate functional performance, which compromises the circularity and health of the material. The construction solutions with plastic waste can be re-used da recycled; however, most of the options did not fulfil the functional requirements. Wood, steel, and aluminium are materials with a remarkable potential for reusing or recycling in construction due to their physical and chemical properties. This was reflected in the ranked construction solutions.

Bio-based materials like Hy-f, Mycoform also tend to be less durable than technical materials as they are generally hydrophilic materials and are prone to the action of fungi. They should remain in dry places or be coated with suitable and healthy materials as a

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solution. The material is coated with a sunflower varnish in the Sunflower Enterprise case study. The same phenomenon happens with fire resistance requirements. Building materials and systems can be optimized through passive fire protection solutions such as healthy paints and coatings, for example, black acacia tannin resin and modified lignin resin (epoxy-lignin)[68].

Despite the use of locally sourced secondary materials can substantially reduce the life cycle impact, impact from primary materials (*e.g.*, painting, resin) that need to be added during production can outweigh the benefits from using secondary materials[102]

The harvest map revealed that all waste flows under the study were generated near the intervention area. The society produces the analyzed waste streams regardless of regional and cultural influences, aside from sunflower and cereal cultivation. Within the raw material needed to replicate the constructive solutions can be easily obtained in the context of the city of Lisbon.

Environmental and functional criteria were qualitatively addressed. However, quantitive values could have been addressed to provide precise analysis, such as a Life-cycle assessment (LCA). This has not been carried out due to the lack of precise production methods and functional characteristics studied solutions, and most are experimental materials. Furthermore, financial and economic profits could also be added to the scheme since material reuse does not result in financial and environmental savings by default.

The authors point out some limitations in using the Macbeth multicriteria analysis tool. The authors are evaluating and classifying the performance of a set of construction and material solutions, whose performance depends not only on itself but also on other members' overall (partition wall) performance and interactions.

Reused and upcycling materials may require substantial transformation processes or need the input of primary materials during the transformation into a condition suitable for use. As building products, this “suitable condition” is demanding and governed by strict regulations, such as energy efficiency and construction safety. The more processes and material inputs required by a reused product, the less likely it will become price-competitive through potential cost savings.

The primary driver for enabling material circularity is cost, technical feasibility, and government policies [[103]. According to [12], the companies' barriers for producing and re-using secondary materials are the difficult sales complex, the limited access to sufficient quantity and quality of used materials, the lack of adequate infrastructure for sorting collection [104].

European and national building codes can promote secondary materials; together with environmental product declarations (EPDs), building certification schemes (*e.g.* BREEAM, Levels, LEED) can assist in making informed decisions [103].

Just recently, European Commission mandates (*e.g.*, M/515) led to an amendment of the EU Building Codes (Eurocodes) to incorporate climate impact concerns. A shift is needed in specifications and guidelines for materials selections, improving certification of recovered materials to reduce uncertainty from the construction contractors and designer and financial investors, and developing incentive strategies to promote using secondary materials over primary materials. Examples are the taxes on primary materials (*e.g.*, aggregates) applied in the majority of EU Member States (EEA, 2016) and reduced Value Added Tax (VAT) for recycled materials in the Czech Republic [103].

6. Conclusions

A sustainable and circular urban metabolism can constantly produce the materials it needs to evolve, without exploiting natural resources. Manufacturers and designers are challenged to create efficient systems where materials exist in various states without ever becoming waste. Design strategies that enable closed decelerated and narrowed material flows will, shortly, become a common practice in this industry, as new production processes, new techniques, construction processes, and new architectural languages incorporate upcycling remanufacture and re-use.

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Designers play a lead role in innovation and must adopt a systematic approach, understanding building composition, assembly, and disassembly routines and their behaviour over time with different social and environmental contexts. Furthermore, designers and construction companies should perceive how the industry manages building material flows, select new upcycled and re-used materials, and analyse their transformation processes.

Despite cascade recovery and upcycling not being widely explored and put into practice, they are competitive strategies that promote proper waste management, introduce resilience in local value chains, and decrease import dependence, closing material flows.

Within this approach, the present article analyzed thirty-five case studies on the re-use and upcycled post-consumer waste and byproducts from various industrial sectors, such as plastic, wood, paper, steel, aluminium, and agricultural waste. A Multi-Criteria Analysis (MCA) was conducted with a dedicated software M-Macbeth (Measuring Attractiveness by a Categorical-Based Evaluation Technique). A methodology considered suitable for the qualitative evaluation and selection of the upcycled and re-used construction materials produced with waste has been developed with qualitative parameters. In detail, parameters of environmental performance, namely, (1) the complexity of transformation processes, (2) the potential of reintroduction in the biological or technological cycle, (3) the toxic content, and (4) the local availability; and parameters of functional performance, namely, (1) the mechanical resistance capacity, (2) the thermal performance, (3) the acoustic performance, (4) the water and moisture resistance, the fire resistance, and the durability).

This study contributes to knowledge by providing a methodology and functional and environmental indicators to select materials building made with domestic and industrial waste qualitatively. The scope of the proposed methodology can be extended in future research and adapted to, for instance, infrastructure projects.However, it presents some limitations that could be addressed by further research. The use of qualitative parameters according to circular principles effectively made it possible to compare different construction solutions. Ten study solutions were suitable for thermal and acoustic isolation, fourteen for coating, and two for structural functions. The analysed alternative materials have good environmental performance. Wood, steel and aluminium waste materials have a remarkable potential for reuse or re-use recycling in construction and Agriculture Waste materials, although their functional limitations show exciting developments in the science and production of new materials.

Furthermore, this research reported that the alternative analyzed materials have good environmental performance and can be used as building materials despite their functional limitations, reflecting the potential of waste as a resource for the construction industry. The transformation process studied introduces new methods and technologies for closed-loop material flows that may reflect the sustainable construction materials and techniques in the coming years. This topic will gain momentum and prominence, providing important guidelines for future new circular production.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Map1: Harvest map.

Author Contributions: Conceptualisation and methodology, SP, VR ,SS and PP; validation, S. P.; formal analysis, PP; investigation, SP; writing—original draft preparation, SP; writing—review and editing, RR, PP and VR; visualisation, SP; supervision, VR, PP, SS and RR; project administration and funding acquisition, RR All authors have read and agreed to the published version of the manuscript.

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Appendix B

Table 1. Identification of the relevant stages of the production chain, authors involved, and places to obtain the plastic waste in Lisbon.

Typology of waste and Symbology			Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Plastic	Urban Waste	PET Bottles	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	• Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul – Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul - Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha •Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar - Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo - Tratamento Resíduos Sólidos Eim - Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda • CIRVA, A.C.E., Porto salvo • Recipolymers, Reciclagem de Polímeros, S.A.; Arranhó
		Various types of plastic waste	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	
		Plastic bags	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	
		Containers to preserve food	Consumption Collection Sorting Waste treatment	Municipal Collectors, Waste Treatment Companies	Public waste treatment companies.	
	Industrial Waste	Sticker Printer Waste	Adhesive Paper Production Final Adhesive Printing and Cutting Waste Collection Waste Treatment	Graphics, Sticker Shops Silk Screen Printing; Municipal Collectors Waste Treatment	Public waste treatment companies.	•Cópia Igual- Centro de Informática, cópias e Papelaria, Lda, Benfica •LET'S COPY - Printshops; Saldanha •Azul e Amarelo, Centro de Cópias e Impressão, Chelas •Copy Campus; Alta de Lisboa •Mar de Cópias, Algés •Diolicopia-Centro De Copias, Lda; Benfica •Zoomcópia, Saldanha •Centro de Cópias Arco Íris de Pedro Proença, Lda, Campo P. •CopyCenter Centro de Cópias; Cid.Un. •Reprografia Comercial Planeta Colorido, Campo Grande

Table 2. Identification of the relevant stages of the production chain, authors involved, and places to obtain the paper waste in Lisbon.

Typology of waste and Symbology			Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Paper	Urban Waste	Miscellaneous Paper Waste	Consumption Collection Sorting Waste treatment	Municipal Collectors Waste Treatment Companies	Public waste treatment companies.	•Europac. Recicla Lisboa; Pero Pinheiro • Centro de Triagem e Ecocentro do Lumiar • Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate • Amarsul – Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) • Valorsul - Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha • Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) • Urbereciclar - Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado • Tratolixo - Tratamento Resíduos Sólidos Eim - Emp. Intermunicipal, S.A; São Domingos de Rana • Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas • Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda •CIRVA, A.C.E., Porto salvo •Gráficas (ver Adesivos Resíduos de Impressoras de Autocolantes)
		TetraPack Packaging	Consumption Collection Sorting Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	
	Industrial Waste	Cardboard Cutting Waste	Cardboard production Cardboard derivatives industry	Graphics, Sticker Shops Silk Screen Printing. Municipal Collectors Waste Treatment	Public waste treatment companies.	• Sacopor-Sociedade de Embalagens e Sacos de Papel S.A, Pior Velho • Cartembal-Cartonagens e Artigos de Papelaria Lda, Benfica •Antunes & Piorla Lda, Charneca • Lamina-Indústria Transformadora de Materiais de Embalagem Lda., Bobadela • Multicaixa - Equipamentos e Consumíveis de • Embalagem, Lda, São Domingos de Rana •Embacar-Embalagens De Cartão Para A Agricultura, Lda., Unhos •Globespan-Indústria De Cartão, S.A., Linda a Pastora •Carbion Portuguesa - Cartão Bi-Ondulado, Lda., Campo P. •Cart - Cartonagens E Transformados De Papel E Cartão, Lda, Odivelas
		Badly printed newspapers	Newspaper Printing	Graphic Printing Companies	Graphic Printing Companies	•Jornal I, Beato •O Jornal Económico •O Emigrante - MUNDO PORTUGUÊS Observador, Campo Grande •Olagarroa Publishing, Lda, Campolide •Diário de Notícias, Benfica •Sábado, Jornal Record e Jornal de Negócios, Benfica •Empresa Gráfica Funchalense, Sintra

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Table 3. Identification of the relevant stages of the production chain, authors involved, and places to obtain the wood waste in Lisbon.

	Typology of waste and Symbology		Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Wood	**Urban Waste**	Doors, furniture, and partitions	Consumption Collection Sorting Second-hand Shops Waste treatment	Resellers, Demolition Companies	Second-hand shops Construction and Demolition Companies Online Platforms	Second-hand shops Móveis Usados E Restaurados, Arrentela ●Antiguidades E Velharias, Almada ●Top Usados, Comercio De Artigos ●Usados, Olival Basto ●Tchiule - Antiguidades e Móveis Usados, Campolide ●Móveis Usados ASO, Vila Cândida ●Móveis Da Casa Zuzarte Lda, Santa Cruz Demolition Companies ●Montagil Demolições, Unipessoal, Lda, Olival Basto ● DOMIPLANA - Terraplanagens E Materiais de Construção, LDAAMGC, UNIPESSOAL, LDA, Beato ●LiftUp DEMOLIÇÕES, S.A., Alverca do Ribatejo ●AMBIGROUP DEMOLIÇÕES, S.A., Arranhó ●MAQUIGAVINHA - Aterros e Desaterros, ●LDAABIMAPE - Sociedade de Construções E Terraplanagens, LDA, Alvalade ●Miguel Duarte Pimentel, Demolições, Lda. ●Demotri, Demolições, Reciclagem e Construção S.A, Odivelas ●Luzipereira - Demolições E Terraplanagens, Lda., Bararena ●Manobras De Génio - Demolições E Terraplanagens, Lda, Camarate
		Fruit boxes	Industry use (fruit transport) Disposal of Boxes, Waste treatment	Fruit producers, fruit distribution companies, super, hyper and mini markets, Collectors, Waste Treatment Companies	Fruit Distribution Companies, Supermarkets and Mini markets	●Antalves - Paletes E Embalagens De Madeira, Lda, Pêro Pinheiro ●Recopal - Recuperação e Comercialização de Paletas, Lda.
		Pallets	Consumption Collection Sorting Waste treatment	Goods distribution companies (retail); Collectors; Waste treatment companies	Public waste treatment companies.	●Renasxer, Frielas ●Manjos Rec. Recuperação e Fabrico de Estruturas de Madeira, Lda, Alverca do Ribatejo e Loures ●Antalves - Paletes E Embalagens De Madeira, Lda, Pêro Pinheiro ●Recopal - Recuperação e Comercialização de Paletas, Lda. ●Marquesapal-comércio De Paletes E Produtos Reciclados Lda
	Industrial Waste	Waste and shavings from the wood products industry	Production of wood-based products, Waste treatment	Wood-based materials industry; Waste Treatment Companies Waste Treatment	Carpentries Wood waste treatment companies	●MDB Gestão de Resíduos Lda Av. Infante Dom Henrique ●AMBIGROUP DEMOLIÇÕES, S.A., Arranhó Carpintarias: ● Carpintel-carpintaria E Construções Lda ● Vítor Luís Santos - Carpintarias e Marcenarias ● Carpintaria E Marcenaria Grilo Lisbonense, Lda, Beato ● Carpintaria Lino & Filhos, Lda., Campo Grande ● Carpintaria Vasco Oliveira, Amoreiras Renasxer, Frielas

Table 4. Identification of the relevant stages of the production chain, authors involved, and places to obtain the wood waste in Lisbon.

	Typology of waste and Symbology		Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Steel and aluminium	**Urban Waste**	Mattress Springs	Consumption Collection Sorting Waste treatment	Waste Treatment Companies (Scrap)	Waste Treatment Companies (Scrap)	●Europac. Recicla Lisboa; Pero Pinheiro ● Centro de Triagem e Ecocentro do Lumiar ● Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate ● Amarsul – Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) ● Valorsul - Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha ● Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) ● Urbereciclar - Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado ● Tratolixo - Tratamento Resíduos Sólidos Eim - Emp. Intermunicipal, S.A; São Domingos de Rana ● Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas ● Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda ●CIRVA, A.C.E., Porto salvo **
		Soft Drink Cans	Consumption Collection Sorting Waste treatmentIndif-ferent	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies.	●Europac. Recicla Lisboa; Pero Pinheiro ● Centro de Triagem e Ecocentro do Lumiar ● Judite Maria Jesus Dias-Operações de Gestão de Resíduos; Camarate ● Amarsul – Ecocentros e Ecoparques (Almada, Moita Lavradio, Montijo, Setúbal, Palmela, Alcochete e Seixal.) ● Valorsul - Valorização Trat. Resid. Sólidos Regiões Lisboa, São João da Talha ● Stericycle Torres Vedras (resíduos industriais equiparados a urbanos) ● Urbereciclar - Reciclagem de Resíduos Sólidos Urbanos Lda, Milharado ● Tratolixo - Tratamento Resíduos Sólidos Eim - Emp. Intermunicipal, S.A; São Domingos de Rana ● Resotrans-recolha e Transporte de Resíduos Sólidos, Lda; Frielas ● Arte-entulhos-recolha E Transporte De Resíduos Sólidos Lda ●CIRVA, A.C.E., Porto salvo
	Industrial Waste	Cutting and sawing waste	Cardboard production Cardboard derivatives industry	Graphics, Sticker Shops Silk Screen Printing; Municipal Collectors Waste Treatment	Public waste treatment companies.	A Agricultura, Lda., Unhos ●Globespan-Indústria De Cartão, S.A., Linda a Pastora ●Carbion Portuguesa - Cartão Bi-Ondulado, Lda., Campo P. ●Cart - Cartonagens E Transformados De Papel E Cartão, Lda, Odivelas
		Industrial containers	Industry (transportation), Collectors, Waste Treatment (Scrap)	Waste Treatment Companies (Scrap)	Waste Treatment Companies (Scrap)	**

Table 5. Identification of the relevant stages of the production chain, authors involved, and places to obtain the

Typology of waste and Symbology			Relevant stages in the production chain	Actors Involved	Places	Potential Places where waste can be obtained in Lisbon
Agricultural waste	**Urban Waste**	Wine Corks	Consumption Collection Waste treatment	Households, Construction and Demolition Companies, Waste Treatment Companies	Public waste treatment companies	Significant quantities of this waste are generated (not mapped) - Availability ≤10 km ● Restaurants ● Coffee Shops Potato Derived Products Production: ● F. B. F. - Fábrica de Batatas Fritas Lda
		Coffee Boring	Consumption Collection Waste treatment	Households, Restaurants; Municipal Collectors; Waste Treatment Companies	Families, Restaurants, Coffee Shops	
		Potato Peel	Consumption Collection Waste treatment	Households, Restaurants; Municipal Collectors; Waste Treatment Companies	Families, Restaurants, Coffee Shops	
	Industrial Waste	Miscellaneous agricultural residues	Producers (agriculture), Disposal in fields or incineration, Derivatives industry y	Producers (agriculture), Derivatives industry)	Derived products companies and cultivation fields	Urban Gardens (some urban gardens were mapped, but there are 40 urban gardens in the Lisbon metropolitan area and most of them are located less than 10 km from the intervention area): ●Parque Hortícola Telheiras ●Parque Hortícola Quinta da Granja ●Parque Hortícola Bensaúde ●Parque Hortícola de Campolide: ●Parque Hortícola do Casal Vistoso Cerealicultura: ●Farinhas Firmos, Moagem de Cereais, Lda, Colares ●Belsuino - Agro-Pecuária da Serra de Cambra, Lda ●GRANEL - MOAGEM DE CEREAIS, S.A. VILA FRANCA XIRA
		Residues from sunflower cultivation	Producers (agriculture), Disposal in fields or incineration, Derivatives industry y	Producers (agriculture), Derivatives industry)	Derived products companies and cultivation fields	Cultivation: ●Parque Hortícola Telheiras Horticultural Park Quinta da Granja Horticultural Park Bensaúde ●Parque Hortícola de Campolide ●Parque Hortícola do Casal Vistoso Derived products companies: ●Sovena Group, Industrial Facilities, Barreiro

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